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Progress in Materials Science 46 (2001) 559–632

Progress in
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Manufacture, characterisation and application of cellular metals and metal foams

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Received 16 August 1999; received in revised form 18 December 1999; accepted 1 January 2000

Abstract

The possibilities for manufacturing metal foams or other porous metallic structures are reviewed. The various manufacturing processes are classified according to the state of matter in which the metal is processed — solid, liquid, gaseous or ionised. Liquid metal can be foamed directly by injecting gas or gas-releasing blowing agents, or by producing super-saturated metal–gas solutions. Indirect methods include investment casting, the use of space-holding filler materials or melting of powder compacts which contain a blowing agent. If inert gas is entrapped in powder compacts, a subsequent heat treatment can produce cellular metals even in the solid state. The same holds for various sintering methods, metal powder slurry foaming, or extrusion and sintering of polymer/powder mixtures. Finally, electro-deposition or metal vapour deposition also allow for the production of highly porous metallic structures. The various ways for characterising the properties of cellular metals are reviewed in second section of this paper. Non-destructive as well as destructive methods are described. Finally, the various application fields for cellular metals are discussed. They are divided into structural and functional applications and are treated according to their relevance for the different industrial sectors. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Cellular metals; Porous metals; Metal foam; Manufacture; Characterisation; Application; Review

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PII: S0079-6425(00)00002-5

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1. Introduction

Foams and other highly porous materials with a cellular structure are known to have many interesting combinations of physical and mechanical properties, such as high stiffness in conjunction with very low specific weight or high gas permeability combined with high thermal conductivity. For this reason, nature frequently uses cellular materials for constructional or functional purposes (e.g. wood or bones). Among man-made cellular materials, polymeric foams are currently the most important ones with widespread applications in nearly every sector of technology. Less known is that even metals and alloys can be produced as cellular materials or foams and that these materials have such interesting properties that exciting new applications are expected in the near future.

Cellular solids and their properties have been described in much detail by Gibson and Ashby [1]. A frequently cited review of cellular metallic materials was published in 1983 [2]. Since then, so many new developments concerning the production, characterisation and application of metal foams have occurred, that an overview of

the current state-of-the-art technology was deemed necessary. Extensive material was compiled in recently published conference proceedings [3–6,298–301], from which some of the examples presented in this article were taken. Other review articles or conference proceedings on cellular materials have concentrated on mechanical properties of cellular materials in general [7,8] or on special aspects of production or application of such materials [9]. A new design guide [10] addresses the properties of metallic foams and provide guidelines of how to properly apply such foams. A website on the internet devoted to cellular models [349] gives up-to-date information about new developments. This article intends to give a current review of the possibilities for manufacturing cellular materials in general, particularly metallic foams, and to provide references to data describing these materials. Moreover, ample coverage is devoted to the discussion of applications of such materials. It is worth noting that more than 80% of the references given in this paper were published after the review article by Davies and Shu Zhen in [2], thus showing to what extent the field has developed.

The term “foam” is not always properly used and shall therefore need to be defined. According to Fig. 1 which lists the designations for all possible dispersions of one phase in a second one (where each phase can be in one of the three states of matter), foams are uniform dispersions of a gaseous phase in either a liquid or a solid [11]. The single gas inclusions are separated from each other by portions of the liquid or solid, respectively. Thus the cells are entirely enclosed by the liquid or solid and are not interconnected. The term “foam” in its original sense is reserved for a dispersion of gas bubbles in a liquid. The morphology of such foams, however, can be

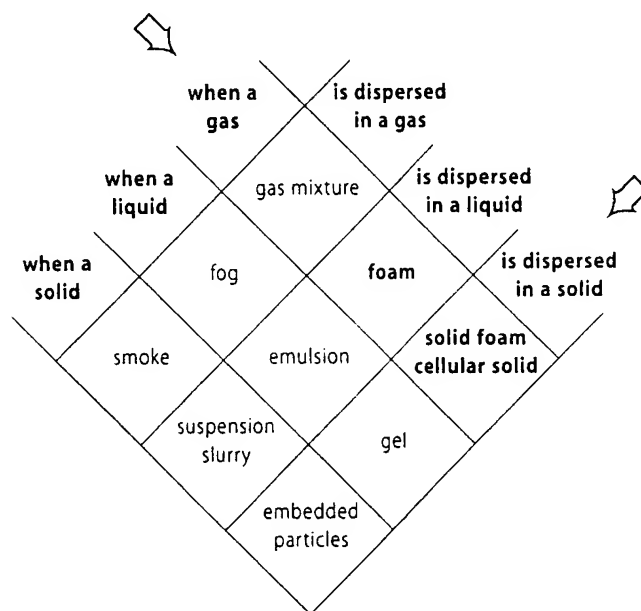


Fig. 1. Dispersions of one phase into a second one. Each phase can be in one of the three states of matter [11].

preserved by letting the liquid solidify, thus obtaining what is called a “solid foam”. When speaking of “metallic foams” one generally means a solid foam. The liquid metallic foam is merely a stage that occurs during the fabrication of the material. Solid foams are a special case of what is more commonly called a “cellular solid”. As in a liquid the minimisation of surface energy only allows for certain foam morphologies, the solid foam, which is just an image of its liquid counterpart, is restricted in the same way. In contrast, cellular solids are not necessarily made from the liquid state and can therefore have nearly any morphology, e.g. the typical open structure of sintered powders. Often such porous structures are also named “foams” although the term “sponge” is likely more appropriate. In this paper some emphasis is placed on the production methods and properties of “true” solid foams, but it is felt that the review would be incomplete without including some methods for producing those cellular metallic structures which are not considered as foams in the strictest sense.

2. Production methods of cellular metallic materials

There are many ways to manufacture cellular metallic materials. Some methods are similar to techniques used for foaming aqueous or polymer liquids, whereas others are specially designed by taking advantage of characteristic properties of metals such as their sintering activity or the fact that they can be electrically deposited.

The various methods can be classified according to the state the metal is processed in. This defines four “families” of processes summarised in Fig. 2, each one corresponding to one of the states of matter: one can start

- (i) from liquid metal,
- (ii) from solid metal in powdered form,
- (iii) from metal vapour or gaseous metallic compounds,
- (iv) from a metal ion solution.

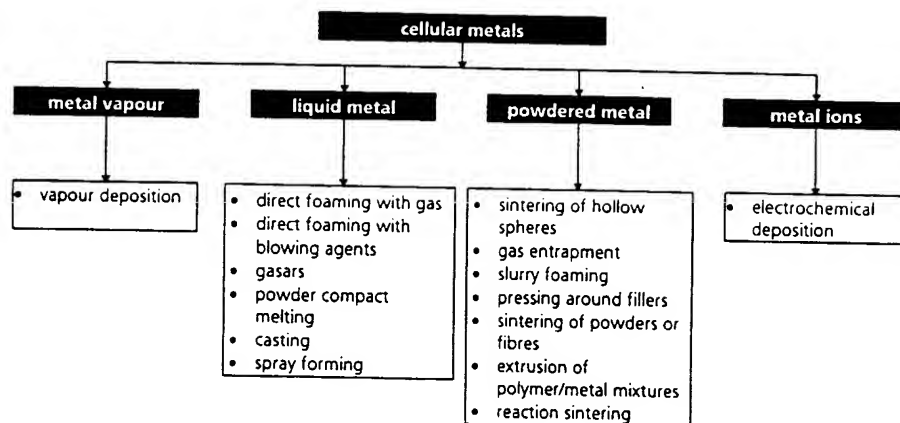


Fig. 2. Overview of the various “families” of production methods for cellular metallic materials.

2.1. Liquid state processing of cellular metals

A first group of processes creates the cellular structure from the liquid metal. The molten metal is processed into a porous material either by foaming it directly, by using an indirect method via a polymer foam or, finally, by casting the liquid metal around solid space holding filler materials which reserve space for what after further processing becomes the pore space. One further possibility is to melt powder compacts containing a gas-releasing blowing agent.

2.1.1. Direct foaming of metals

Metallic melts can be foamed directly under certain circumstances by creating gas bubbles in the liquid. Normally, gas bubbles which are formed in a metallic melt tend to quickly rise to its surface due to the high buoyancy forces in the high-density liquid, but this rise can be hampered by increasing the viscosity of the molten metal. This can be done by adding fine ceramic powders or alloying elements which form stabilising particles in the melt.

Numerous attempts to foam liquid metals in this way — mostly aluminium, magnesium, zinc or alloys based on one of these metals — have been undertaken in the 1960s and 1970s [12–19]. Although some quite good metal foams were produced, the material did not find its way into real industrial application. It is not entirely clear whether the process control was still inadequate to yield foams of satisfactory and reproducible quality and price, or whether the need for materials such as aluminium foams was not big enough 30 years ago. In the past 10 years, however, a number of new developments have taken place so that nowadays some improved production routes are available.

Currently, there are two ways for foaming metallic melts directly: to inject gas into the liquid metal from an external source, or to cause an in-situ gas formation in the liquid by admixing gas-releasing blowing agents to the molten metal.

It is interesting to recall that one of the earliest patents written in the 1940s suggested using a second metal as a blowing agent, e.g. mercury for foaming aluminium [20]. This second metal is vapourised when heating the aluminium to its melting point and creates pores this way.

2.1.1.1. Foaming by gas injection. The first way for foaming aluminium and aluminium alloys is currently being exploited by Hydro Aluminium in Norway and by Cymat Aluminium in Canada (the latter's using methods and patents originally developed by Alcan International) [21–28]. According to this process as depicted in schematical form in Fig. 3, silicon carbide, aluminium oxide or magnesium oxide particles are used to enhance the viscosity of the melt. Therefore, the first step requires the preparation of an aluminium melt containing one of these substances. The problem to be solved resembles the one encountered in making ordinary metal matrix composites (MMCs), namely the problem of wetting the particles by the melt and of achieving a homogeneous distribution of the reinforcing particles [29,30]. A variety of aluminium alloys is used, e.g. the casting alloy AlSi10Mg (A359) or wrought alloys such as 1060, 3003, 6016, or 6061 [28,31].

The liquid MMC melt is foamed in a second step by injecting gases (air, nitrogen, argon) into it using specially designed rotating impellers or vibrating nozzles. The function of the impellers or nozzles is to create very fine gas bubbles in the melt and distribute them uniformly. This is an important requirement because only if sufficiently fine bubbles are created, a foam of a satisfactory quality can be obtained. The resultant viscous mixture of bubbles and metal melt floats up to the surface of the liquid where it turns into a fairly dry liquid foam as the liquid metal drains out. The foam is relatively stable owing to the presence of ceramic particles in the melt. It can be pulled off the liquid surface, with a conveyor belt, and is then allowed to cool down and solidify. Care has to be taken not to damage the pore structure by shearing the foam too much while it is still semi-solid. Before solidification, the semi-solid foam can be flattened by means of one or more top-mounted rolls or belts to yield a foam slab with closed and fairly even upper and lower skins [32,33]. The resulting solid foam is in principle as long as desired, as wide as the vessel containing the liquid metal allows it, and typically 10 cm thick. Two foam samples are shown in Fig. 4.

The volume fraction of the reinforcing particles typically ranges from 10 to 20% and the mean particle size from 5 to 20 μm [21,34]. The selection of particle size and content has been carried out empirically. Too high or too low contents or particle sizes create the problems addressed in Fig. 5. The particles help to stabilise the foam by mechanisms which are discussed in the literature [35–37]. It is widely accepted that the accumulation of particles on the cell walls plays a key role in this stabilisation process. Firstly, the particles increase the surface viscosity, thus retarding drainage in films [35]. Secondly, the particles are partially wetted by the melt. It has been derived [36] that the wetting angle has to be in a certain range to ensure that

- (i) the bubble/particle interface is stable when the bubble rises through the melt, i.e. the particles are not stripped off the bubbles,
- (ii) that the particles on the interface lower the total energy of a pair of bubbles with particles in between, i.e. stabilise bubble/particle/bubble interfaces.

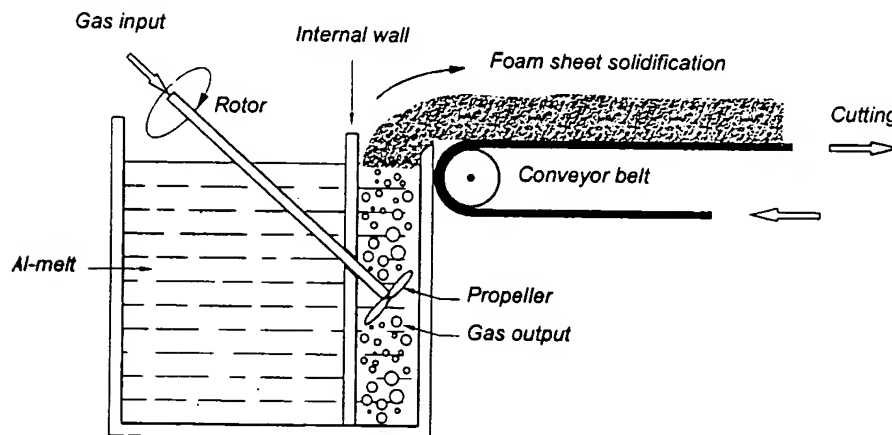


Fig. 3. Direct foaming of melts by gas injection (MMC foams) [28].

For insufficient wetting (high contact angle) as well as for too good wetting (too low contact angle) there is no stabilisation effect. In principle, from the known wetting angles of ceramic particles with a given melt particles can be selected which have an optimum stabilisation effect [36].

The porosities of aluminium foams produced this way range from 80 to 98%, corresponding to densities between 0.069 and 0.54 g/cm³, average pore sizes from 25 down to 3 mm, and wall thicknesses from 50 to 85 μm [27,31]. The average cell size

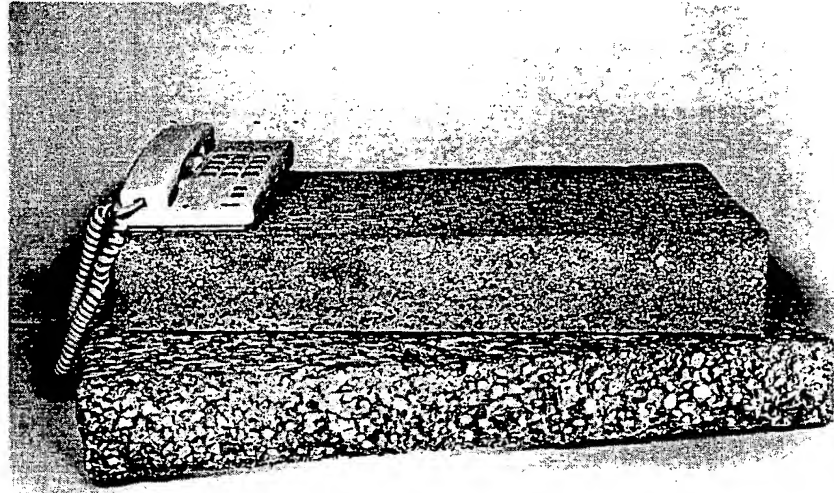


Fig. 4. Foam slabs of two different densities and cell sizes produced by the gas injection method (sample: Hydro Aluminium, Norway).

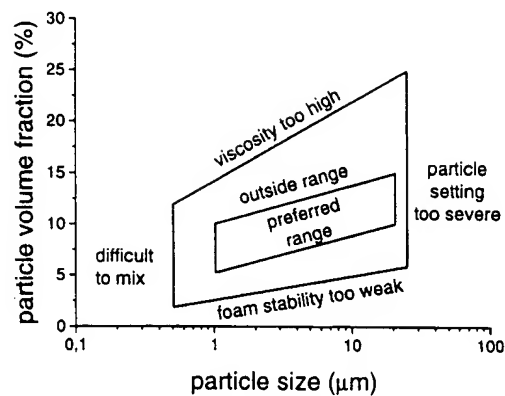


Fig. 5. Selection of particle size and content for foaming MMC melts [21,35].

is inversely related both to the average cell wall thickness and to the density and can be influenced by adjusting the gas flow, the impeller speed or nozzle vibration frequency, and other parameters [31]. In foamed slabs there is usually a gradient in density, pore size and pore elongation which is a natural consequence of gravitationally induced drainage [38]. Moreover, the shearing forces of the conveyor belt lead to diagonally distorted cells in the final product. This obviously has a pronounced effect on the mechanical properties which become anisotropic [39]. The situation could be improved by pulling off the foam vertically [40]. The foamed material is either used in the state as it comes out of the casting machine, having a closed outer surface, or is cut into the required shape after foaming. Owing to the high content of ceramic particles, machining of MMC foams can be a problem.

Advantages of the direct foaming process include the large volume of foam which can be continuously produced and the low densities which can be achieved. MMC foams are therefore probably less expensive compared to other cellular metallic materials. The Canadian company Cymat is about to complete a production line which will deliver 1000 kg of foam per hour in widths up to 1.5 m and thicknesses between 2.5 and 15 cm [41]. Hydro Aluminium produces slabs 70 cm wide, 8–12 cm thick, and up to 2 m long at a rate of 500–600 kg/h [28]. A possible disadvantage of the direct foaming process is the eventual necessity for cutting the foam, thereby opening the cells. Also, the brittleness of the MMC foam due to the reinforcing particles contained in the cell walls is in general an unwanted side effect of the foaming technique. Attempts for making shaped parts by casting the semi-liquid foam into moulds [42] or by shaping the emerging foam with rolls have been undertaken [32,33], thus trying to eliminate one of these disadvantages. The structure and the properties of metal foams manufactured by direct foaming have been investigated and are given in the literature (see Table 1, column 4). The largest part of the literature is on mechanical properties, but some acoustical and fire resistance data are also available.

In order to avoid the deleterious effects of stabilising additives to metallic melts, it was suggested to foam pure, additive-free metallic melts with inert gases. In order to keep viscosity low, the foaming process has to take place at temperatures very close to the melting point. This can be done by bubbling gas through a melt which is constantly cooled down in a continuous casting process [55]. The bubbles are then caught in the solidifying liquid and form a foam-like structure.

2.1.1.2. Foaming with blowing agents. A second alternative way for foaming melts directly is to add a blowing agent to the melt instead of blowing gas into it [12–14,16,17]. The blowing agent decomposes under the influence of heat and releases gas which then propels the foaming process. This is explained in Fig. 6 for a modern version of the process [56–58] which has been used in small-scale commercial exploitation since 1986 at Shinko Wire, Amagasaki, Japan with production volumes reportedly up to 1000 kg foam per day. In this technique, calcium metal is added to an aluminium melt at 680°C. The melt is stirred for several minutes during which its viscosity continuously increases by a factor of up to five [58–60], owing to the

Table 1
Properties of metal foams — sources for experimental data (mostly aluminium, some data on magnesium and steel foams): numbers correspond to references

Class	Sub-class	Property	Hydro/Alcan-like	"Alporas"-like	"Foaminal/Alulight"-like	"Duocel"-like
General		Cell size distribution		58,61,63	137–139	
		Density distribution		58	138–141	
		Cell morphology	31,43–46,303	45,58,63–66, 302–304	45,303	46,63,178,323
Mechanical properties		Microstructure	31,35,38,43, 45,47	38,45,67	45,136,142, 310	70,178
	Elastic	Young's modulus	31,39,47,48, 303,324	48,63,303,324, 327	132,137,138, 143–150,303	63,175,178, 303,323
		Shear modulus	31,44		48	175
	Anelastic	Loss factor		329	146,148,150–153,320	
		Uniaxial compression	31,35,39,43,45 47–50,303,324	38,45,48–50,58, 60,61,63,64, 67–70,90,91, 303,304,324, 328,329	48,115,138–140,144,146, 147,150,154 155,303,337	63,175,178, 303,318,323, 328
	Plastic	Strength				
		Tensile strength	48–50,303	48–50,58,60,63, 67,303,304,314, 329	147,155,303	175,303
		Shear strength	44,48–50	48–50,67,328		
		Bending strength	50	67	50,146,147, 156	
		Bi and multi-axial yielding	51	71,305,325		71,305,325
	Strain rate dependence	31	63,68,72,308, 321	157,158,310	68,157,179, 180,308,313	
	Density gradient effects	39		141		
	Energy absorption	31,35,43,47,48, 50	48,50,64,307	48,50,138, 139,146,150, 159		

(continued on next page)

Table 1 (continued)

Class	Sub-class	Property	Hydro/Alcan-like	"Alporas"-like	"Foaminal/Alulight"-like	"Duocel"-like
Other properties		Fatigue	52	73,302,322	149,160–163, 316,326 163	73
		Toughness				
		Creep		74		
		Temperature dependence	35			
	Composite behaviour	Heat treatment		64	138,145,147 154,164	319
		Sandwich panels		50,69,73,75, 309	50,69,129, 315,317	
		Foam filled sections	53,54,306,311, 312		127,146,154, 159,165–167, 277,317	
	Electrical	Electrical conductivity	47	58,60	132,137,138	175
		Electromagnetic shielding		67	138,150	
	Thermal	Thermal conductivity	47	50,67	50,138,150	175,330
Thermal expansion			67	156		
Acoustic	Fire/heat resistance	47				
	Corrosion	Sound absorption	47	58,60,65–67 50,76	138,150,168 50,317	

formation of calcium oxide (CaO), calcium–aluminium oxide (CaAl_2O_4) or perhaps even Al_4Ca intermetallics which thicken the liquid metal [38,331]. Fig. 7 shows the effect of stirring on the viscosity of aluminium melts with various calcium additions see [59,60]. For the actual foam production, usually 1.5–3 wt% Ca are added. After the viscosity has reached the desired value, titanium hydride (TiH_2) is added (typically 1.6 wt%) which serves as a blowing agent by releasing hydrogen gas in the hot viscous liquid. The melt soon starts to expand slowly and gradually fills the foaming vessel. The foaming takes place at constant pressure. After cooling down the vessel below the melting point of the alloy the liquid foam turns into solid aluminium foam and can be taken out of the mould for further processing. The entire foaming process can take 15 min for a typical large batch [58]. It has been shown that a careful adjustment of process parameters leads to very homogeneous foams [61]. In fact, the foams produced in this way — trade name “Alporas” — seem to be the most homogeneous aluminium foams currently available, not counting, e.g., the cast structures described in Section 2.1.4. The pore morphology of such a foam is shown in Fig. 8. There is an empirical relationship not only between average cell diameter and the viscosity of the melt but also between the final foam density and viscosity

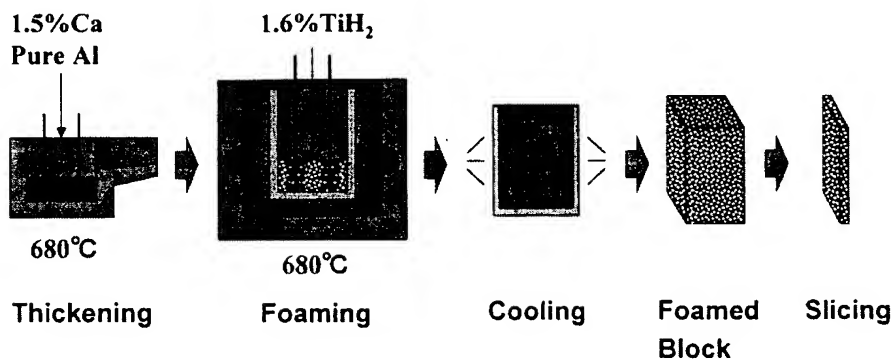


Fig. 6. Direct foaming of melts with blowing agents (“Alporas”-process) [58].

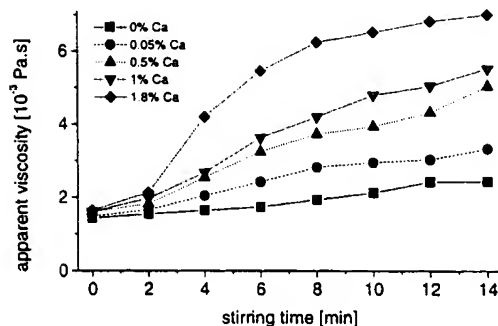


Fig. 7. Influence of stirring time on the viscosity of an aluminium melt after admixture of calcium metal [59].

[59,333]. In the literature, zirconium hydride (ZrH_2) has also been recommended as a blowing agent for the production of aluminium foams with preferred concentrations between 0.5 and 0.6 wt% [62] and foaming temperatures ranging from 670 to 705°C.

Foamed aluminium is produced in typical batches of 2050 × 650 × 450 mm by Shinko Wire. The mass of one cast foam block is approximately 160 kg, corresponding to an overall density including outer skins of 0.27 g/cm³. Typical densities after cutting off the sides of the block are between 0.18 and 0.24 g/cm³, with the average pore size ranging from 2 to 10 mm. One observes density gradients along both the horizontal and vertical direction of the cast foam block, with the lowest densities occurring in the top middle part of the block. The blocks are usually cut into sheets of the required thickness (5–250 mm, standard thickness 10 mm).

Mechanical and some other properties of “Alporas” have been measured. Epoxy resin bonded sandwich structures based on “Alporas” have been manufactured and characterised. Alporas foams have been surface treated with water or chemical vapour to enhance corrosion resistance [76] (see Table 1, column 5).

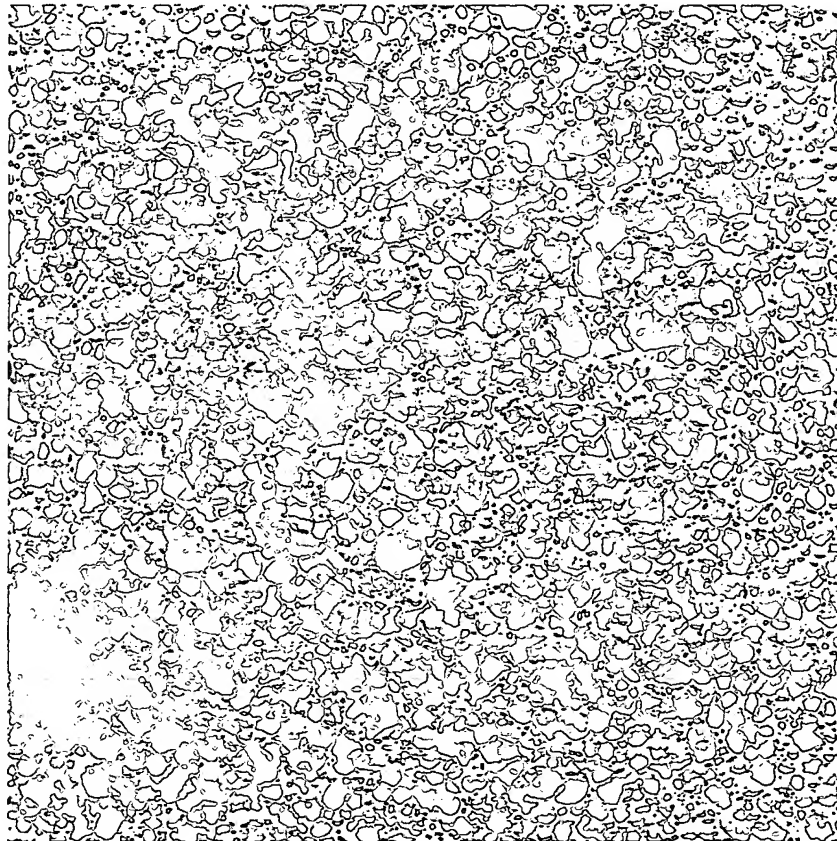


Fig. 8. Pore structure of aluminium foamed by adding TiH_2 . Section shown is 80 × 80 mm² in size (sample: Southeast University Nanjing, China).

“Alporas” foam is reportedly more expensive than the MMC foams described earlier. Some efforts to extend the process towards a continuous foam fabrication or to the production of complex-shaped foam parts have been undertaken [77]. It has been claimed that even ferrous alloys can be foamed in a way similar to aluminium and other low melting alloys by injecting a mixture of a blowing agent and a foam “stabiliser”, e.g. tungsten powder, into a ferrous melt [78].

Instead of using calcium for adjusting the melt properties, a viscosity enhancement of molten aluminium can also be obtained by bubbling oxygen, air or other gas mixtures through the melt (causing the formation of alumina) [16,79], by adding powdered alumina, silicon carbide [329], aluminium dross [80] or scrap foamed aluminium [81], or by using metallic viscosity enhancing additives [82]. However, the proper adjustment seems to be quite difficult and requires complicated temperature cycles and mechanical agitation. Quite promising results have been obtained by using manganese oxide (MnO_2) powder with a mean particle size of 20 μm for viscosity enhancement [64].

Some of the problems with admixing metal hydride powders to a melt could be circumvented by first preparing a low melting eutectic precursor alloy, e.g. Al–Mg, in which the blowing agent can be incorporated without decomposition, then foaming a higher melting alloy, e.g. pure aluminium, by admixing said precursor alloy with it [83]. Further aspects of this liquid foaming process are described in patents by Jarema [84,85] and Niebylski [15,18,19,86–88]. An interesting variant was proposed by Ptashnik [89]: the blowing agent is added to a liquid alloy at a temperature just above its solidus temperature but below the decomposition temperature of the blowing agent. After intense stirring the metal is allowed to solidify in a mould of the desired shape. The actual foaming takes place in a second step when the composite is heated to a temperature above the decomposition temperature of the blowing agent. The evolving gas then produces bubbles and the volume increases. This method resembles some of the powder compact melting methods described in Section 2.1.3 and shall be reconsidered there.

Foams produced in the 1970s by one of the early versions of direct foaming of melts with blowing agents were mechanically characterised by various authors (aluminium: [90,91], zinc: [92]).

2.1.2. Solid–gas eutectic solidification (“gasars”)

A method developed about a decade ago [93,94] exploits the fact that some liquid metals form a eutectic system with hydrogen gas. By melting one of these metals in a hydrogen atmosphere under high pressure (up to 50 atm), one obtains a homogeneous melt charged with hydrogen. If one then lowers temperature, the melt will eventually undergo a eutectic transition to a heterogeneous two-phase system, “solid + gas”. If the composition of the system is sufficiently close to the eutectic concentration, there will be a segregation reaction at one temperature. Because the eutectic composition depends on the system pressure, the external pressure and the hydrogen content must be co-ordinated. Removal of heat from the melt causes directional solidification. As the solidification front advances through the liquid, typically at velocities ranging from 0.05 to 5 mm/s, the hydrogen content near the

solidification plane increases and gas bubbles are formed. The process parameters have to be chosen such that the bubbles do not float out into the remaining liquid and disappear but remain near the solidification zone and are entrapped in the solid [95]. The resulting pore morphologies are largely determined by the hydrogen content, the pressure over the melt, the direction and rate of heat removal, and the chemical composition of the melt. Generally, largely elongated pores oriented in the direction of solidification are formed. They only appear spherical when observed in this direction as shown in Fig. 9. Pore diameters range from 10 μm to 10 mm, pore lengths from 100 μm to 300 mm, aspect ratios from 1 to 300 and porosities from 5 to 75% [94]. The pore size distribution is non-uniform because of concurrent growth of small and large pores and coalescence. Pores may be conical or even corrugated. Heterogeneous pore nucleation and pore growth in gasars is further described and discussed in Ref. [94]. For the porous materials formed by solid–gas eutectic solidification, the word “gasar” was coined meaning “gas-reinforced” in a Russian acronym.

One possible practical implementation of the gasar process is depicted in Fig. 10. An autoclave is required in which the melt can be produced, charged with hydrogen and finally directionally solidified. If the casting vessel is cylindrical, radial and axial pores can be made [93,97] depending on how the sample is cooled. Gasars based on nickel [95], copper [98–102,334], aluminium [103,104] and magnesium [105] are described in the literature. Beside these metals, the technique seems to work for a

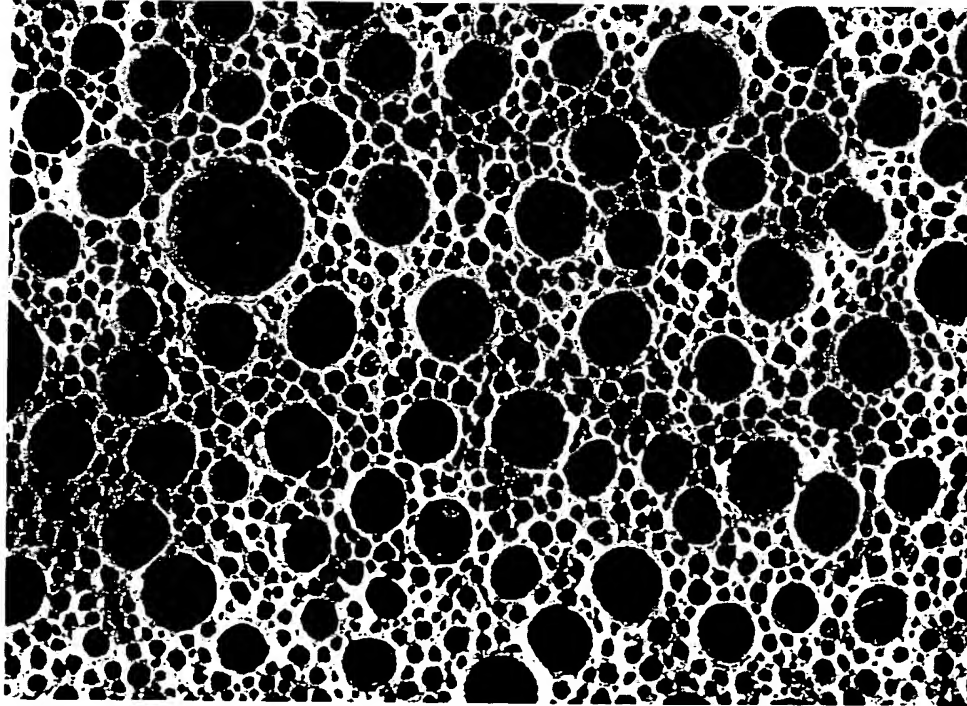


Fig. 9. Pore structure of a “gasar”. Surface normal to direction of pores is shown [96].

variety of steels, cobalt, chromium, molybdenum and even ceramics. The pore morphology and microstructure of gasars has been characterised [98–101]. However, the homogeneity of gasars is sometimes unsatisfactory and further improvements are needed to allow for applications of the material. The mechanical properties of gasars — strengths in compression [102] and tension [101,104], Young's modulus and Poisson's ratio [104] — have been characterised.

2.1.3. Powder compact melting technique

Foamed metals can be produced by a method developed at Fraunhofer-Institute in Bremen (Germany) [106–112]. The fundamental ideas for the process are comparatively old [113,114], but the method has been brought to a level of sophistication only recently to allow for manufacturing foams or foam components of satisfactory quality. The method is often called “powder metallurgical” because the starting materials are metal powders but since the actual foaming takes place in the liquid state the method shall be described in this section.

The production process begins with the mixing of metal powders — elementary metal powders, alloy powders or metal powder blends — with a blowing agent, after which the mix is compacted to yield a dense, semi-finished product (see diagram in Fig. 11). In principle, the compaction can be done by any technique that ensures that the blowing agent is embedded into the metal matrix without any notable residual open porosity. Examples of such compaction methods are hot uniaxial or isostatic compression, rod extrusion or powder rolling [106,107]. Which compaction method is chosen depends on the required shape of the precursor material. However, extrusion seems to be the most economical method at the moment and is therefore the preferred way [116,117]. Rectangular profiles with various cross-sections are usually made from which thin sheets can then be obtained by rolling. The manufacture of the precursor has to be carried out very carefully because any residual porosity or other defects will lead to poor results in further processing.

Heat treatment at temperatures near the melting point of the matrix material is the next step. The blowing agent, which is homogeneously distributed within the

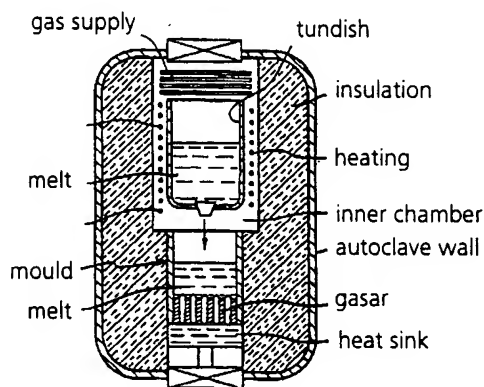


Fig. 10. Apparatus for making “gasars” [93].

dense metallic matrix, decomposes. The released gas forces the compacted precursor material to expand, thus forming its highly porous structure. The time needed for full expansion depends on temperature and the size of the precursor and ranges from a few seconds to several minutes. Fig. 12 shows expansion curves of an aluminium/ TiH_2 powder compact. The volume of the expanding foam is shown as a function of time together with some morphologies in various stages of expansion. An expansion maximum is shown which corresponds to a fairly uniform foam morphology, after which the foam collapses. The degree of maximum expansion, and therefore, the

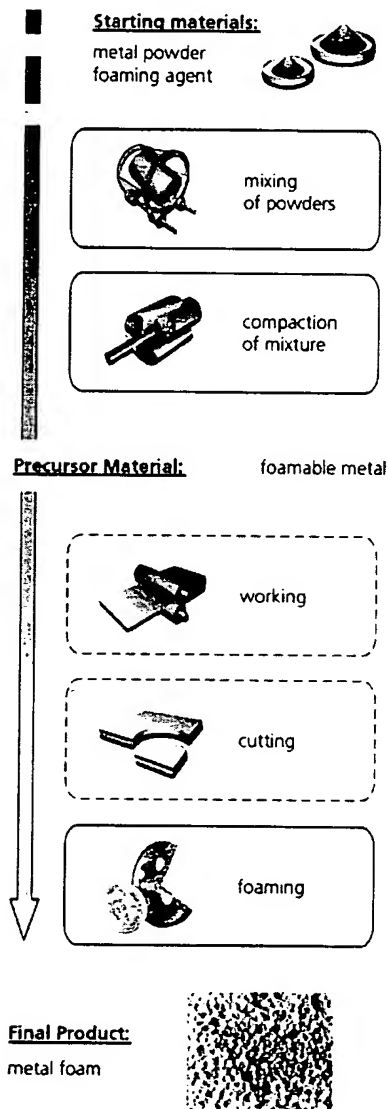


Fig. 11. Powder compact melting process [106,115].

density of the solid metal foam, can be controlled by adjusting the content of blowing agent and several other foaming parameters, such as temperature and heating rates. For zinc and aluminium alloys, titanium or zirconium hydride (TiH_2 , ZrH_2) is used as a blowing agent. Steels can be foamed with carbonates such as SrCO_3 [119–121,335,336]. If metal hydrides are used as blowing agents, a content of less than 1% is sufficient in most cases.

The method is not restricted to aluminium and its alloys: tin, zinc, brass, lead, gold and some other metals and alloys can also be foamed by choosing appropriate blowing agents and process parameters. The most common alloys for foaming, however, are pure aluminium or wrought alloys, such as alloys 2xxx or 6xxx. Casting alloys such as AlSi7Mg (A356) and AlSi12 are also frequently used because of their low melting point and good foaming properties, although in principle virtually any aluminium alloy can be foamed by carefully adjusting the process parameters. Fig. 13 shows a typical cross-section of a lead foam. One sees that the distribution of cell sizes and shapes exhibits a certain randomness which is typical for such a process.

Foaming a piece of precursor material in a furnace results in a lump of metal foam with an undefined shape unless the expansion is limited in certain directions. This is done by inserting the precursor material into a hollow mould and expanding it by heating. In this way, near-net shaped parts can be obtained. It can be advantageous to adapt the shape of the piece of precursor material to the geometry of the mould in which it is foamed to improve flow conditions during foaming. Quite complicated parts can be manufactured by injecting the still expanding foam into suitable moulds [122]. This process is explained by the schematical sketch in Fig. 14. Accordingly, a piece of foamable precursor material is heated up to a temperature near its melting point in a closed recipient. After foaming has been initiated and the precursor has

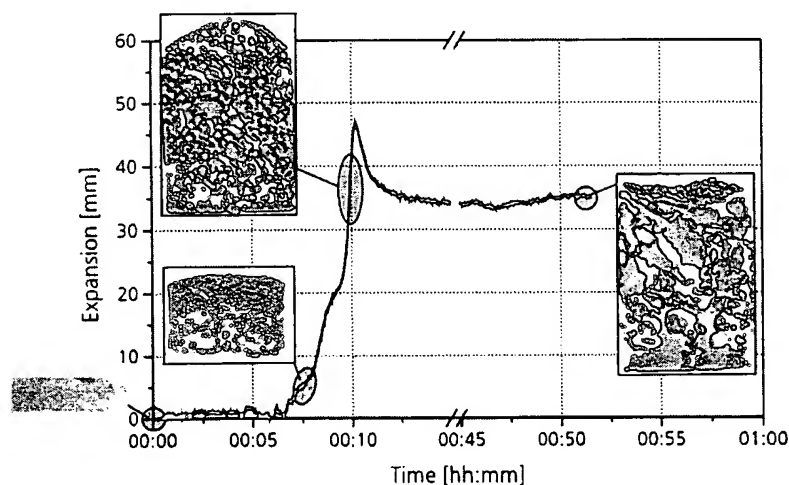


Fig. 12. Expansion behaviour of aluminium/ TiH_2 compacts when foamed at 750°C [118]. The volume of a metal sample as a function of time and images of four different expansion (including the unexpanded precursor which is 9 mm in height and 32 mm in diameter) are shown.

become semi-solid, the mass is injected into a mould by a movable piston and allowed to complete its expansion in the mould. The pore structure of the foamed parts may suffer from defects if the process is not carefully controlled [123]. However, the process could be an important step towards an economical mass production of complicated volume parts.

Sandwich panels consisting of a foamed metal core and two metal face sheets can be fairly easily obtained by bonding the face sheets to a piece of foam with adhesives. Alternatively, if pure metallic bonding is required, conventional sheets of metal — aluminium or steel — are roll-clad to a sheet of foamable precursor material [111]. The resulting composite can be deformed in an optional step, e.g. by deep drawing. The final heat treatment, in which only the foamable core expands and the

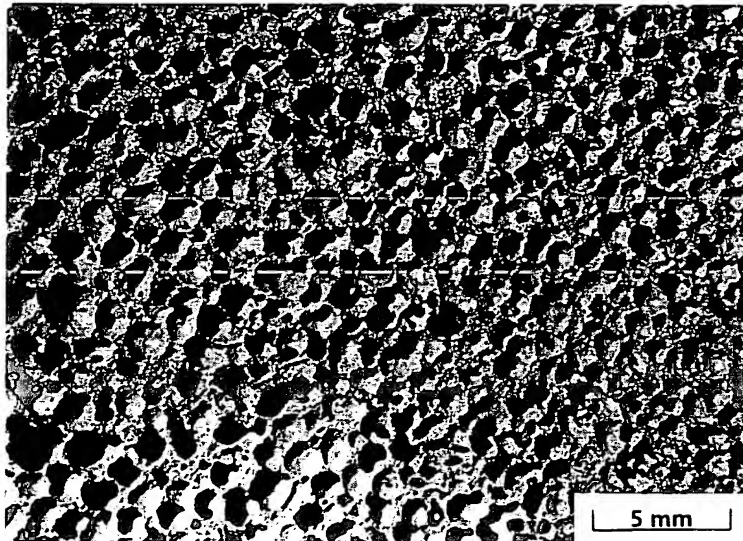


Fig. 13. Cross-section of a lead foam made by powder compact melting [115].

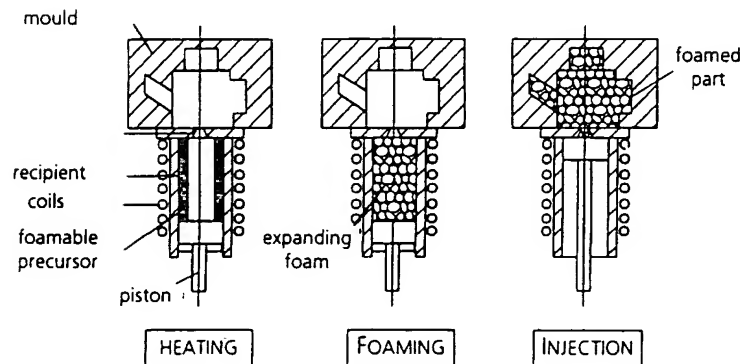


Fig. 14. Foam injection process [122].

face sheets remain dense, then leads to sandwich structures such as the one shown in Fig. 15. Aluminium foam can be combined with steel [124] or titanium face sheets as well as with aluminium face sheets. In the latter case, care has to be taken not to melt the face sheets during foaming, e.g. by choosing alloys with different melting points of the core material and the face sheets. A large aluminium/aluminium foam sandwich was developed in a joint effort by the German car maker Karmann in Osnabrück and Fraunhofer-Institute in Bremen for a concept car in which structural aluminium foam applications were demonstrated [125]. One such part is shown in Fig. 16. Such sandwiches are 3D-shaped, up to 2 m in length and about 1 m in width (see Section 4.2.1 for a discussion of their application).

Tubes or almost arbitrarily shaped columns can be filled with aluminium foam in various ways:

1. The easiest way is to insert a rod of foamable precursor material into the column to be filled and to place both into a furnace. The precursor material will start to foam and eventually fill the section completely. The disadvantage of this method is that only tubes with a significantly higher melting temperature as compared to the material to be foamed — e.g. steel tubes if aluminium is foamed — can be used.
2. An alternative is to insert a foamable hollow section closely fitting into the section to be filled with foam instead of using a simple rod. Then the foam can

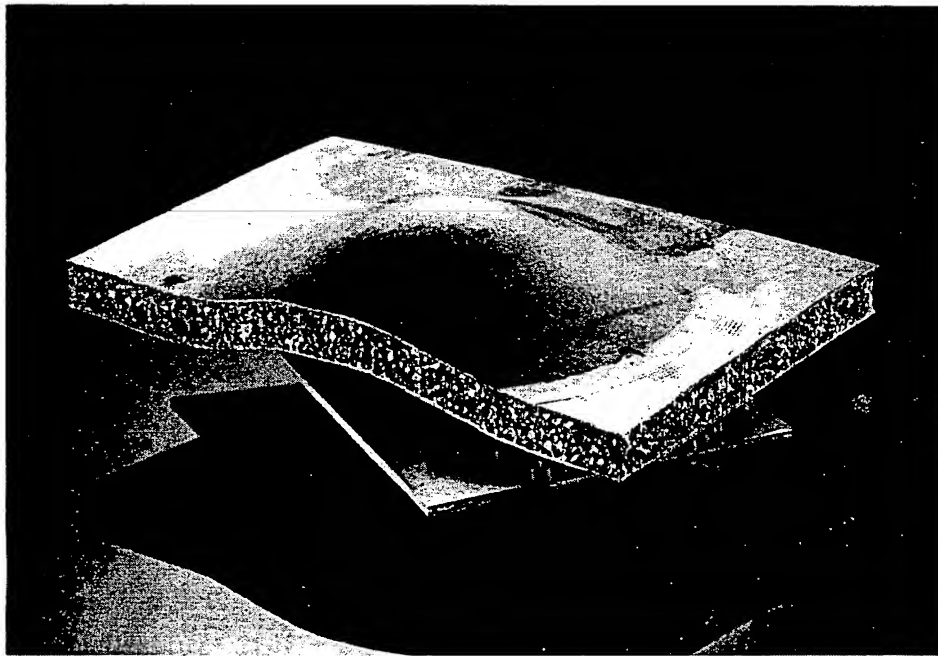


Fig. 15. Sandwich panel having an aluminium foam core (thickness 12 mm) and two steel face sheets (source: Fraunhofer and Studiengesellschaft Stahlanwendungen).

- only expand towards the centre of the outer section and lends it a certain mechanical support during foaming. Moreover, the thermal contact between section and foam prevents the section from getting too hot during foaming.
3. In a third option, two concentrically arranged tubes are co-extruded to a composite in which the two components have a metallurgical bond. For the inner tube, foamable material is chosen whereas the outer tube is a normal aluminium alloy. In the subsequent foaming step, the inner layer expands towards the centre of the tube and eventually fills it.
 4. Yet another way for making composites is to produce an aluminium foam component with a dense outer skin by thermal spraying of aluminium onto an aluminium foam pre-shaped body, thereby creating a composite. One such sample is shown in Fig. 17. Of course, this technique is not restricted to tubes and almost any foamed body can be coated.
 5. Finally, if one uses aluminium foam parts as cores in conventional sand-casting one can create structural composites in which the foamed core remains completely enclosed in the cast component [127,128].

Composites of metal foam and ceramics can also be manufactured. Aluminium foam (AlSi12) can be diffusion bonded to alumina plates at 500°C applying a pressure of 100 kPa in vacuo [129]. Alternatively, an aluminium alloy 6061 foam has been bonded in situ to alumina plates by letting the foam expand between two ceramic layers at a fixed distance [130].

Most metal foam parts can be manufactured in commercially available furnaces provided that their temperature is sufficiently uniform. However, for a cost effective

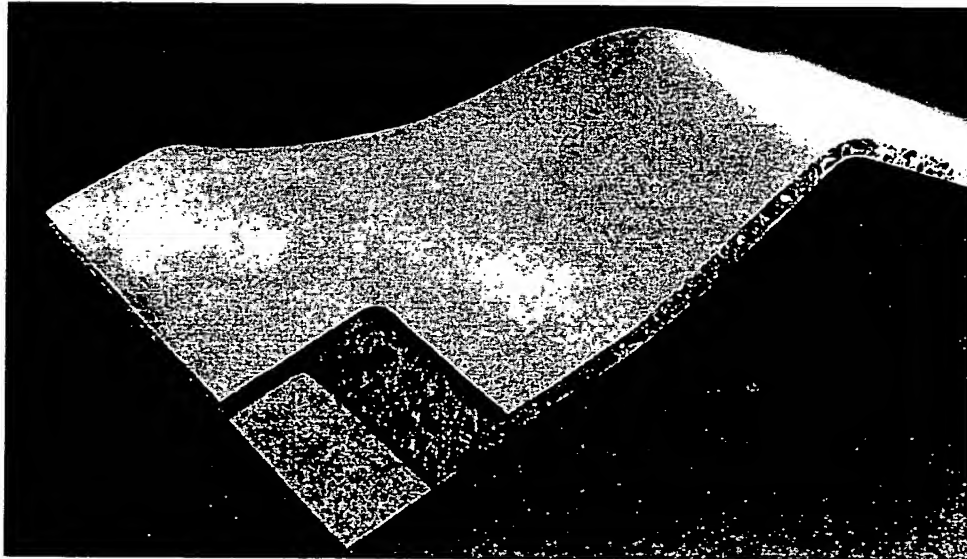


Fig. 16. Aluminium/aluminium foam sandwich obtained by foaming a roll-clad precursor containing TiH_2 as blowing agent (source: Karmann and Fraunhofer). Thickness of sandwich is about 10 mm.

mass production of parts, it is preferable to use continuous furnaces in which foamable precursor material — in appropriate moulds or as clad sheets without mould — is conveyed through various heating zones where it is foamed and finally cooled. Even batchwise production could be improved by using moulds which can be charged and uncharged automatically. This would avoid having to cool down the moulds to ambient temperatures after each foaming cycle. The mould could be operated between the foaming temperature and a lower temperature at which the foam has just become solid. This way much energy could be saved, the time for making one foamed part could be dramatically reduced, and the amount of labour would be minimised [332].

A useful tool for filling hollow sections with metal foam would be a mobile foam injection device in which a foamable wire would be melted and foamed continuously inside the hollow structure to be filled. Advantages would include continuous operation, localised foam filling and a low thermal effect on the section material.

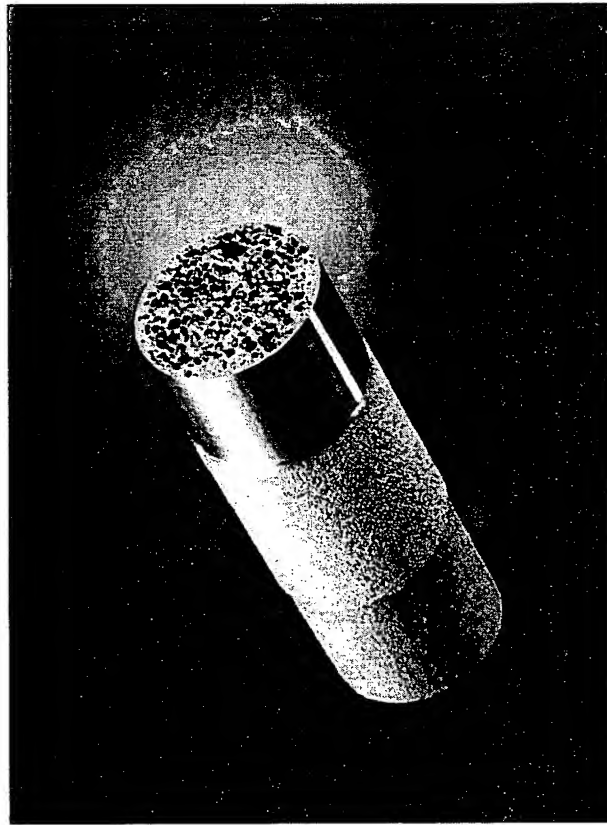


Fig. 17. Aluminium foam coated with an aluminium skin (source: Fraunhofer and RWTH Aachen, part is about 60 mm long). Lower section: aluminium foam prior to coating, middle part: after thermal spraying, upper section: after finishing.

More information about the powder compact melting technique can be found in the literature [115,118,131–136]. Foams made by this technique have been characterised thoroughly with respect to their properties and extensive data can be found in the literature (see Table 1, column 6).

A recent development concerns a modification of the powder compact melting process. One tries to make a foamable precursor material by incorporating titanium hydride particles directly into an aluminium melt instead of using powders [37,169–171]. To avoid premature hydrogen evolution the melt has to be quickly cooled down below its melting point after mixing. Alternatively, titanium hydride can be passivated by a heat treatment to slow down its decomposition [170]. Foams with a highly uniform pore morphology have been obtained this way. It is interesting to note that some of these ideas were in existence already 40 years ago [172].

The powder compact melting method is now in the stage of a small-scale commercial exploitation by the German companies Schunk GmbH and Honsel AG and the Austrian companies Mepura and Neuman. For aluminium foams made this way, the trade names “Foaminal” and “Alulight” have been coined.

2.1.4. Casting methods

2.1.4.1. Investment casting with polymer foams. Foams can be manufactured from molten metal without directly foaming the metal. This is shown in the schematic description of Fig. 18. According to this process, a polymer foam, e.g. polyurethane foam, is used as a starting point. If the polymer foam has closed pores, it has to be transformed into an open porous one by a reticulation treatment. The resulting polymer foam with open cells is then filled with a slurry of sufficiently heat resistant material, e.g. a mixture of mullite, phenolic resin and calcium carbonate [173] or simple plaster [174]. After curing the polymer foam is removed by thermal treatment and molten metal is cast into the resulting open voids which replicate the original polymer foam structure. Application of pressure and heating of the mould may be necessary if no filling of the narrow cavities with the liquid metal can be achieved in simple gravity casting. After removal of the mould material (e.g. by pressurised water), a metallic structure is obtained which is an exact replicate of the original polymer foam. Difficulties in this process include achieving a complete filling of the

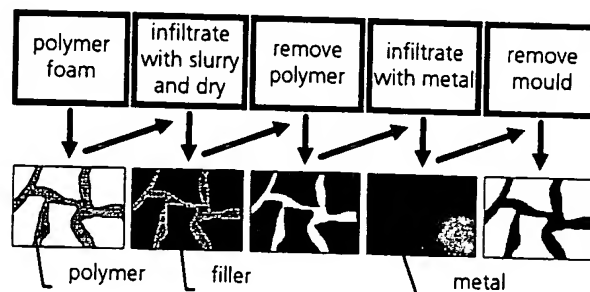


Fig. 18. Production of cellular metals by investment casting.

filaments, controlling the usually directional solidification and removing the mould material without damaging the fine structure too much.

Fig. 19 shows a micrograph of a cellular aluminium material made by this technique. Such foams have been sold by ERG in Oakland (USA) under the trademark “Duocel” [175] for many years and reportedly also by a Japanese company [63]. Various grades are available ranging from 2 to 16 pores/cm (5–40 ppi). Complex shaped parts can be fabricated by pre-forming the polymer foam. Some examples of aluminium foam components made at the University of Aachen [176] are shown on the right-hand side of Fig. 19. Aluminium alloys such as 6101 or AlSi7Mg (A356) are usually used [175] but other metals, like copper [175] and magnesium [174], can also be processed. Of course, the densities and foam morphologies of the final metal product are determined by the polymer precursor. Porosities typically range from 80 to 97%. Some mechanical and thermal data and flow properties can be found in the literature (see Table 1, last column). Prices of ERG material have been reported to be high (“US\$ 10 per cubic inch of foam”), probably owing to rather low annual production volumes of about 8 m³, but recent developments in casting technology promise a mark down of this price by up to two orders of magnitude [176,177].

2.1.4.2. Lattice block materials. Investment casting can be used to obtain ordered, highly porous metals called “Lattice block materials” (LBMs). LBMs are repeated cells consisting of straight beams each connecting two nodes. The structures are perfectly regular with nodes that are all connected to, e.g., 12 or 14 struts. Such structures can be made from pre-fabricated injection moulded polymer elements in a comparably similar manner by bonding such elements together layer by layer with adhesives. The resulting structure is then used as a model for the following investment casting step which yields a metallic material that represents exactly the highly ordered polymer precursor. In principle, any castable material can be used, e.g. aluminium A356 or stainless steel [181]. Lattice spacings between 6.5 and 25 mm and strut diameters between 1.5 and 3.8 mm are common. The main advantage of

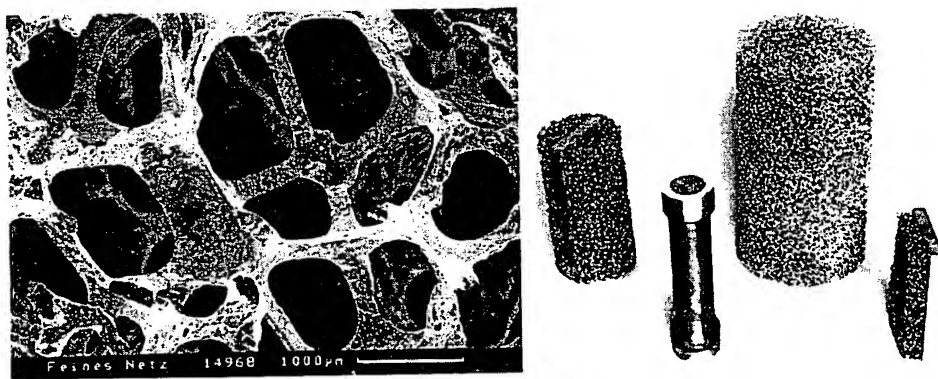


Fig. 19. Left: SEM image of “Duocel” [175], right: some parts made by investment casting [176] (large cylinder is about 40 mm in diameter).

metallic LBMs are their mechanical properties which are close to the theoretical optimum limit and which are easily predictable and reproducible.

2.1.4.3. Casting around space holder materials. Light-weight porous metals can be produced by casting liquid metal around inorganic or even organic granules or hollow spheres of low density, or by introducing such materials into a metallic melt. The granules either remain in the metallic product after casting — yielding what is called a “syntactic foam” — or are removed by leaching in suitable solvents or acids or by thermal treatment (see Fig. 20). This can be done successfully if the content of space holding fillers is so high that all the granules are interconnected. Vermiculite or fired clay pellets [182], soluble salts [183–185], loose bulks of expanded clay granules, sand pellets [186,187], foamed glass spheres or aluminium oxide hollow spheres [188–193] can serve as inorganic filler material. Polymer spheres can be used as organic space holders if the solidification of the melt is sufficiently fast. The latter requires high pressure infiltration, e.g., in a die-casting machine [194].

Pre-heating of the bulk of space holders is usually necessary to avoid premature solidification of the melt, especially when the heat capacity of the bulk is high or infiltration pressure is low. Owing to the high surface tension of liquid metals, wetting of the granules might cause a problem, since, in general, the interstices between the granules will not be filled completely. Creating a vacuum between the granules or pressurising the melt is therefore an important pre-requisite for infiltration. Space-holding salts are removed by leaching in water. Sand pellets can be easily removed if the binder decomposes under the influence of heat [186], whereas the polymer spheres are brought out by thermal pyrolysis. A wide range of metals can be processed this way, including aluminium, magnesium, zinc, lead, tin, etc. Parts of a predefined shape can be fabricated by designing a mould of the desired geometry. In all cases, the morphology of the materials created can be characterised as “sponge-like”.

The diagram in Fig. 21 shows a possible way for making syntactic foams [192,193]. In this case, commercially available alumina hollow spheres of 2.1–3.6 mm diameter and 100–200 mm wall thickness were used. The spheres were stacked

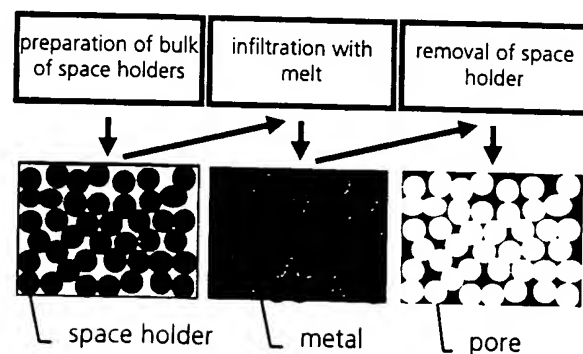


Fig. 20. Production of cellular metallic materials using space-holding fillers.

into a steel mould and vibrated to ensure a high packing density. The bulk of spheres was then pressure infiltrated by a magnesium melt at about 700°C. The structure is very uniform and the foam properties are nearly isotropic. Sandwich panels can also be made [191]. For this, the ceramic spheres are placed into a pre-fabricated skin structure between two sheets of metal, and are then infiltrated by the melt. The skin is melted at its surface to be able to achieve a metallurgical bond. Alternatively, the skin can be produced by placing a pre-sintered bulk of hollow spheres into a mould and casting the outer skin structure and the porous core at the same time.

One of the main advantages of using space holders is the close control of the pore size distribution which is given by the distribution of particle sizes of the filler granules. This contrasts with the pore size distribution of the materials foamed by the processes described in Sections 2.1.1–2.1.3 where a statistical distribution of pores is found. On the other hand, the maximum porosities which can be achieved using space holders are limited to values below 80%, whereas the methods presented in Section 2.1.1 allow for porosities up to 98%.

The pore morphology of an open porous aluminium material made by the high pressure infiltration version of the space holder technology is shown in Fig. 22. The filler material has been removed completely in this case and the density is as low as 1.1 g/cm³. Some components manufactured from the material are shown in Fig. 23 which also illustrates that composites of foam and dense aluminium can be produced. Threads were cut into the dense sections of the material to make a component which could be attached to the gas outlet of a pneumatic device to damp pulsations.

2.1.5. Spray forming ("Osprey process")

Spray forming is a method which allows for processing a variety of different metals and alloys. Metallic melt is continuously atomised and a spray of fast flying small metal droplets is created. The droplets are collected on a substrate where they grow to a dense deposit in a given shape, e.g. a billet, sheet or tube, provided the process parameters are appropriately chosen. The characteristics of spray-formed materials include low oxide content, fine grain size or a high content of metastable alloy phases [195]. This combination of properties usually cannot be obtained by

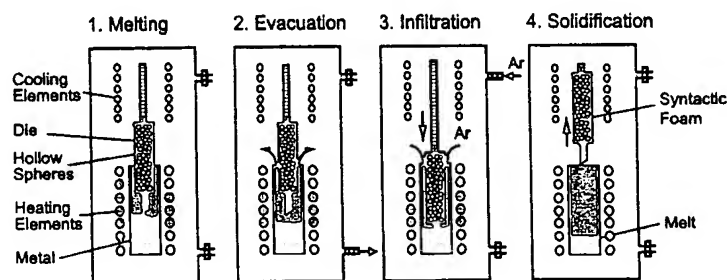


Fig. 21. Process steps for making syntactic foams [192,193].

conventional casting methods. One feature makes the spray process appear especially attractive: the possibility for modifying the properties of the deposit by injecting powders such as oxides, carbides or pure metals into the spray and allowing them to react with or be wetted by the liquid metal droplets and to be incorporated into the metal as it is deposited on the substrate. This way MMCs can be made if the added powders are carbides or oxides. If the injected powders are substances which decompose upon contact with the molten metal and release large amounts of gas, they may generate pores in the deposit (see schematical description in Fig. 24). This effect — usually undesired — can be used to make porous metallic materials. Kelley et al. [197] have investigated the formation of porosity in CuSn6 alloys by injecting BaCO_3 powder. Banhart et al. [198] have created porous steel by injecting silicon oxide or manganese oxide into a carbon steel spray, thus creating large amounts of carbon monoxide in the deposition zone in a chemical reaction of the type $\text{SiO}_2 + 2\text{C} \rightarrow \text{Si} + 2\text{CO}$. The porosities achieved in this way can range up to 60% but pore morphologies still lack uniformity.

2.2. Solid state processing of cellular metals

Instead of a molten metal, solid metal in powdered form can be used for making cellular metallic structures. The powder remains solid during the entire process and merely goes through a sintering treatment or other solid state operations. This is

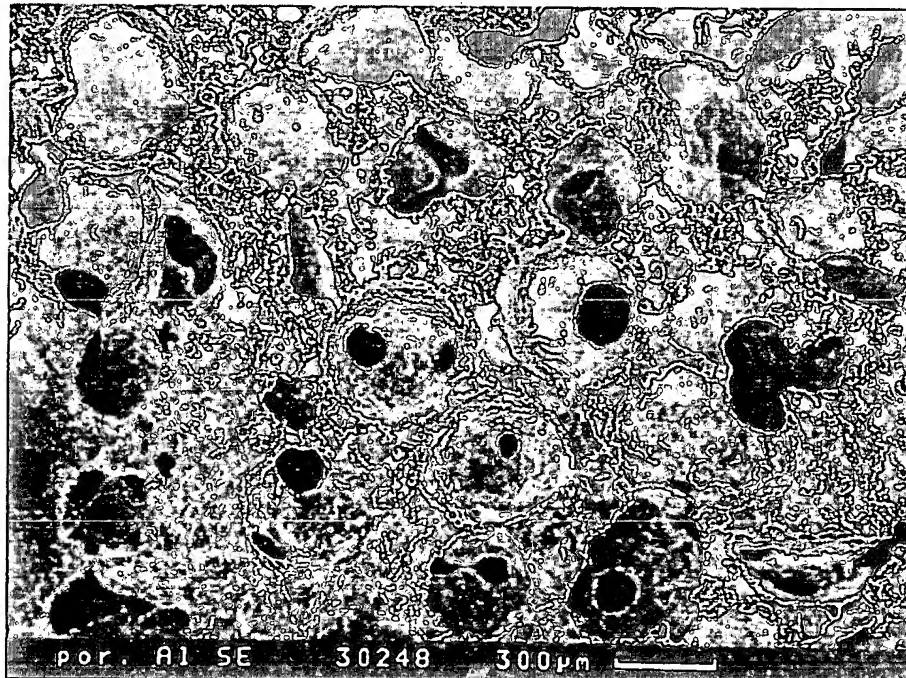


Fig. 22. Cellular aluminium material made by using space-holding fillers. Density 1.1 g/cm^3 .



Fig. 23. Parts made from the material shown in Fig. 22. The compact sections of the parts form a structural composite with the porous sections (source: Fraunhofer). The length of the tallest cylindrical component is 130 mm.

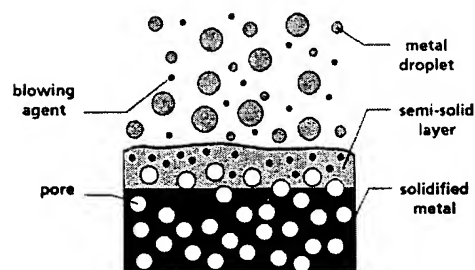


Fig. 24. Manufacture of metal foam by spray forming [196].

crucial for the morphology of the resulting cellular structure since only in the liquid state surface tension does cause a tendency towards the formation of closed pores, whereas sintered porous products show the typical open morphology of isolated, more or less spherical particles connected by sinter necks. Nowadays, simply sintering loose bulks of powders or fibres is the easiest way to obtain porous metals and an established production route in P/M industry. More advanced technologies may

create porosity by entrapping gas in a powder compact, by using space-holding filler materials or hollow spheres or, finally, by foaming metal powder slurries.

2.2.1. Sintering of metal powders and fibres

Today porous metallic products are being mass produced for a multitude of applications. A large variety of metals is used, including titanium or superalloys, although bronze and stainless steel account for most market applications. In general, the production of porous structures consists of various steps: powder fractioning and preparation, compaction or moulding, and sintering [199]. Loose pack or gravity sintering is mostly used for bronze (Cu89Sn11). Sinter temperatures are around 820°C, and porosities between 20 and 50% can be achieved, whereas strengths are comparatively low. One such material is shown in Fig. 25. Axial die-compaction, isostatic pressing or roll compaction of the powders prior to sintering increase the strength of the green part by cold welding of the particle to its contact areas. Subsequent sintering then further increases density and strength, and parts characterised by a very fine porosity can be manufactured (see Ref. [200] and references within).

Wet powder spraying consists of spraying fine powder/binder slurries containing a carrier liquid onto a porous support, then drying and diffusion bonding this coating in a vacuum or under a hydrogen atmosphere. In this way, very fine porosities down to 1 µm can be achieved [199].

Making porous metals from aluminium alloy powders or granules is more difficult than using the metals already mentioned because aluminium is usually covered by a dense oxide layer which prevents the particles from sintering together. To circumvent this problem, one may deform the mixture of powders or granules during pressing to break up the oxide films and to create metallic bonding between the particles. Alternatively, sintering aids may be employed such as copper, silicon or magnesium powders that form a low melting eutectic alloy during sintering at 595–

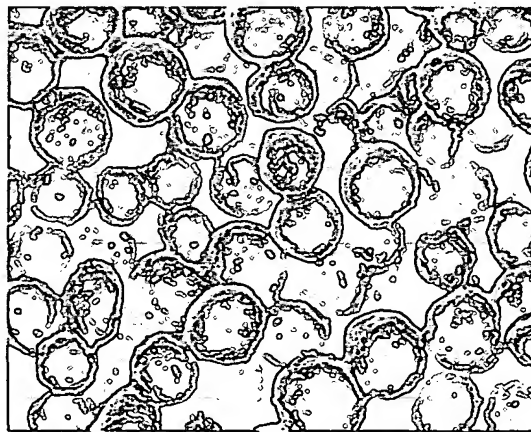


Fig. 25. Porous sintered bronze made from particles with about 100 µm diameter [200].

625°C. For pressureless sintering the aluminium granules and the sintering aids can be milled to initiate mechanically induced alloying processes prior to sintering.

Replacing powders by metal fibres opens new possibilities for making porous metal structures. A great variety of metals can be produced as fibres and processed to sintered products [201,202] which are commercially available.

2.2.2. Gas entrapment technique

Cellular metals can be manufactured in analogy to the process described in Section 2.1.3 but without using a blowing agent and without melting the metal. For this, powders are compressed to a dense precursor material. During compaction gas is allowed to be entrapped in the material [203]. Heating the precursor material in a second step then leads to metal expansion due to the internal pressure created by the entrapped gas. The expansion takes place in the solid state and is therefore not an actual foaming but rather a solid state creep process.

The method has been applied for making porous titanium structures by the aircraft manufacturer Boeing (USA) [204]. Fig. 26 shows a possible implementation of the process [205]. Titanium powder is filled into a can that is first evacuated and outgassed, then refilled with argon gas at pressures from 3 to 5 atm [206]. The can is then sealed and isostatically hot pressed during which the structure is densified. The argon gas is compressed accordingly and forms uniformly dispersed pores which are under a high internal pressure while they occupy less than 2% of the total volume. The densified material can finally be worked into a near-net shape and converted

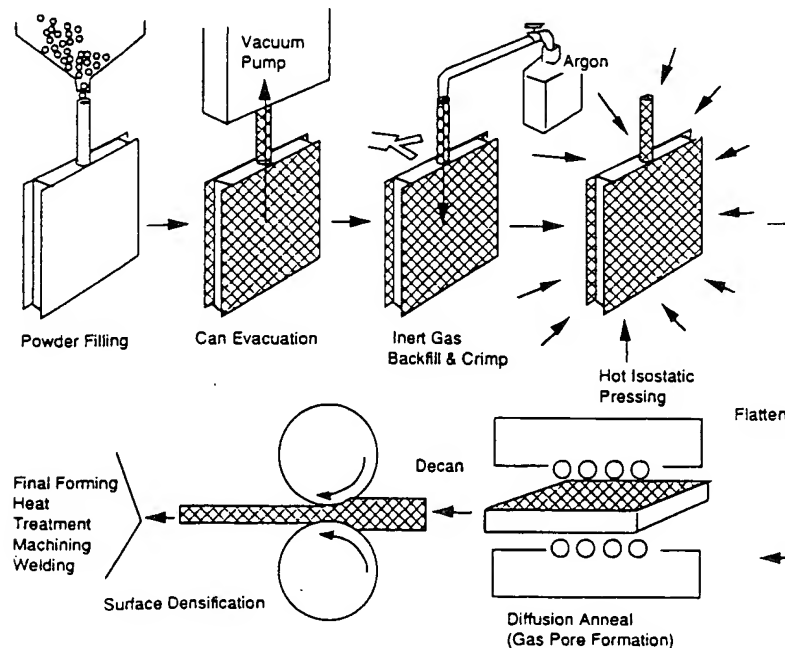


Fig. 26. Gas entrapment technique [205].

into a cellular material by means of an appropriate annealing treatment. Typically, this annealing step takes place at 0.6 times the melting temperature of the respective alloy and takes 6–24 h. During annealing the gas pores slowly expand, thus lowering their internal pressure until an equilibrium between the gas pressure and the strength of the metal at the annealing temperature has been reached. A porous body with 20–40% unconnected porosity is obtained. Typical pore diameters range from 10 to 100 μm . Theoretical considerations show that no more than 50% porosity can be expected for the gas entrapment technique [207,338]. The walls of the can containing the powder can have a dual function: besides sealing the powder, they form a dense outer layer on the cellular core after annealing thus allowing for manufacturing sandwich structures consisting of a foamed core and two face sheets. The cross-section of one such sandwich is shown in Fig. 27. It was cut out of a large 1.2×2.1 m sheet which was hot rolled for densification prior to expansion. Its relative density is about 66% of bulk titanium. Some elastic mechanical properties of porous titanium materials manufactured by the gas entrapment technique can be found in Ref. [208].

2.2.3. Foaming of slurries

Metallic foams can also be produced by preparing a slurry of metal powders, blowing agents and some reactive additives. The slurry is poured into a mould after mixing and left there at elevated temperatures. Under the influence of the additives and the blowing agent, the slurry turns viscous and starts to expand as gas begins to evolve. If sufficient stabilising measures have been taken, the expanded slurry can be preserved and dried completely after which it is sintered to yield a metal foam with considerable strength. Foams have been produced from aluminium powders using orthophosphoric acid with aluminium hydroxide or hydrochloric acid as a blowing agent [209]. Relative densities down to 7% have been achieved. Still, problems with insufficient strength [210] and cracks in the foamed material may occur.

Slurries can be used in an alternative manner to make an open porous metallic foam. In this case, an open porous polymer foam is dipped into a slurry containing a mixture of silver and silver oxide powder [211]. Next, the foam coated this way is dried and heated up to a temperature where the polymer is burnt out and the metal powder particles start to sinter together, thus forming a rigid cellular metal structure.

2.2.4. Cellular metals based on space-holding fillers

In analogy to the processes described in Section 2.1.4, porous sponge-like materials can be obtained by using filler materials and metal powders. The difference from Section 2.1.4 is that the bulk of space-holding material is now filled with fine metal powder instead of being infiltrated with liquid metal (Fig. 28). The metal powder is either filled into a “dry” bulk of fillers [339], or a suitable solvent [212,213] or even an organic binder [214] may be used to mix the space holders and the metal powders. Ceramic particles or hollow spheres, polymer grains or hollow polymer spheres, salts or even metals can be used as space holders. The filled bulk is then either simply compacted at room temperature or, if the space holders are heat resistant, pressed at elevated temperatures to improve compaction and to start sintering processes between the metal powder particles. In both cases, a composite is obtained which

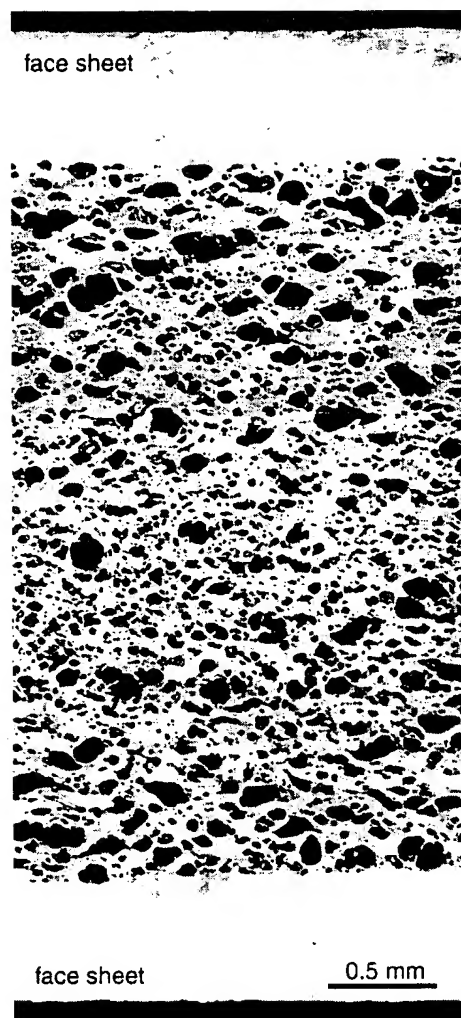


Fig. 27. TiAl6V4 sandwich structure with a porous core made by the gas entrapment technique [206].

consists of a metal matrix with embedded filler granules. If the metal content is sufficiently low, it is possible to remove the space holder material almost completely in a further process step because the network formed by the filler material is interconnected. This can be done by thermal treatment, leaching, or by use of an aqueous solvent. A final sintering step can be applied to further densify the porous metallic network.

Titanium foams, e.g., have been manufactured by one of the following three ways:

1. One way is to use polymer spheres as space holders. Vibratory loading of a bulk of polymer spheres with titanium powder is followed by cold pressing, removing the polymer by thermal treatment, and finally by sintering (see Fig. 29, left).

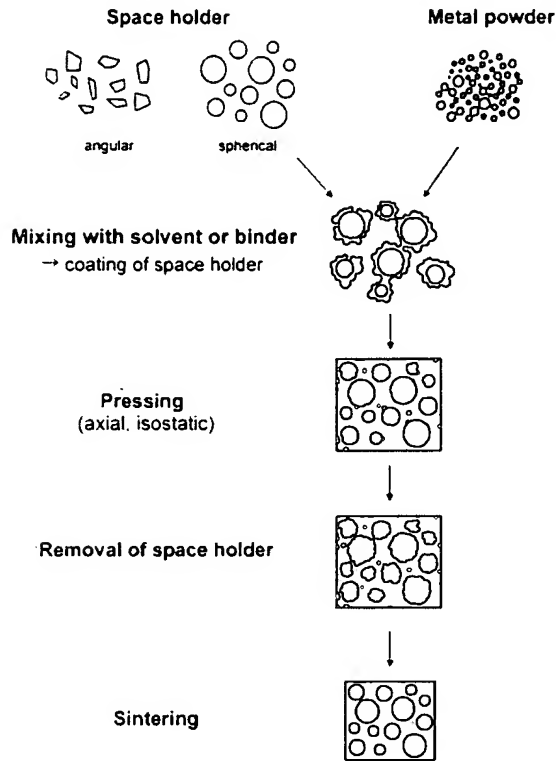


Fig. 28. Space holder technique for making porous metallic structures from metal powders (adapted from Ref. [213]).

2. Alternatively, magnesium metal granules can be used as a filler. In this process, a bulk of such granules is filled with titanium powder after which the mixture is hot pressed at temperatures well below the melting point of magnesium. The magnesium granules are then removed by evaporation at temperatures up to 1400°C [215] at which sintering processes between the titanium particles take place simultaneously. The advantage of magnesium is its low boiling point (1107°C) and its complete immiscibility with titanium (see Fig. 29, right).
3. Finally, highly porous titanium has been manufactured by using carbamide particles with grain sizes from 0.4 to 2.5 mm as space holder to which fine titanium powder with grain sizes lesser than 45 μm was added after moistening the carbamide with petrolether. The mixtures were pressed at 166 MPa and heat treated first at 170°C, then finally at 1400°C. Porosities up to 70% were observed [212]. Stainless steel (316L) and some nickel based superalloys were also processed to cellular solids with porosities ranging from 60 to 80% [213].

2.2.5. Metallic hollow sphere structures

Hollow spheres made of copper, nickel, steel or titanium can be used to create highly porous structures by bonding the individual spheres together by sintering.

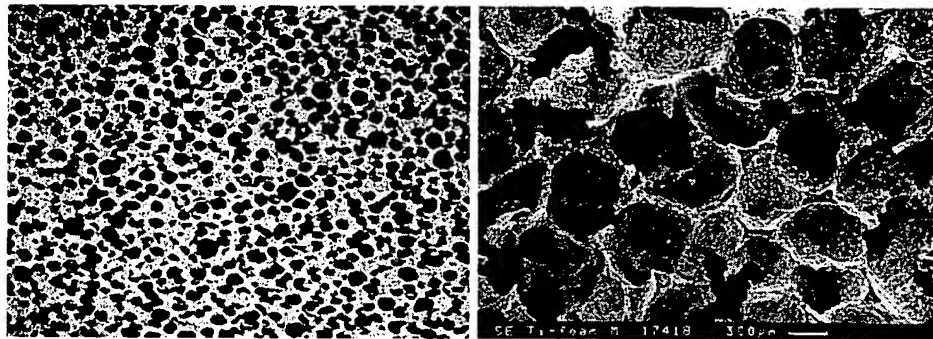


Fig. 29. Cellular titanium made by powder metallurgy using polymer (left) or magnesium granules (right) as space-holder (source: Fraunhofer).

The metallic hollow spheres can be made in various ways: either by combined chemical and electrical deposition of the respective metal onto polymer spheres which are removed in a following step [217], or by coating polymer spheres (e.g., of polystyrene) with a binder/metal powder suspension and subsequently sintering the metal to obtain a dense metal shell while the polystyrene is removed (see Fig. 30) [218]. A further possibility is to blow metal powder, metal oxide powder or metal hydride powder slurries up to micro-spheres using coaxial nozzles, dry the spheres in a drop tube, and then sinter or deoxidise these dried spheres [219,220]. Finally, another possibility is to atomise metallic melts and choose the parameters in a way that hollow spheres [221] are formed.

Usual sphere diameters range from 0.8 to 8 mm, wall thicknesses from 10 to 100 μm . Hollow spheres can be used to manufacture light-weight materials with open and closed porosity with both ordered and disordered arrangements of the cells:

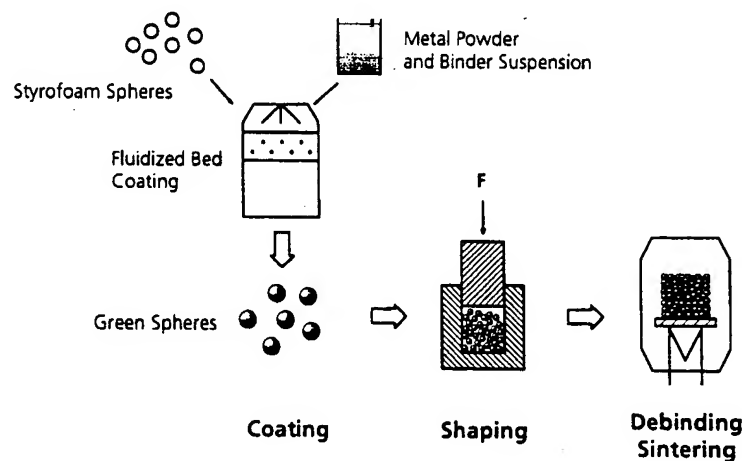


Fig. 30. Styrofoam coating process for making hollow sphere structures [218].

open structures are obtained by sintering a bulk of hollow metal spheres thus creating sintering necks between adjacent spheres [217]. If the spheres are arranged in a regular way on a Bravais lattice, e.g., before sintering — this can be done by using wax honeycombs as a stacking aid — an ordered material is obtained. By applying forces during sintering the spheres are deformed to polyhedral bodies leading to an increase of sintering contacts but also to a reduction of the degree of open porosity. Using a bonding slurry the contact between the individual spheres can be improved [222]. One way is to bond oxide spheres together with an oxide slurry and to carry out the deoxidation and the sintering in one step [222]. Alternatively, one starts from slurry coated polystyrene spheres which are bonded together. Debinding and bonding is then achieved in one step [218,340]. Spheres with not too thin walls are used for open structures.

A typical cellular metal obtained by one of these ways could be made of Ti-6Al-4V alloy, contain 36% interstitial porosity, 44% porosity in the sphere cavity and have a solid volume in the sphere walls of 20%, thus having an overall density of 0.9 g/cm³ [219]. An example of an open sintered hollow sphere structure after and before a uniaxial deformation is shown in Fig. 31.

Closed structures can be obtained by filling the interstices between the spheres with metal powder followed by a sintering treatment [223]. Thin walled spheres are sufficient in this case. Sandwich type structures can be manufactured in a straightforward way by sintering the bulk of hollow spheres between two face sheets, thus

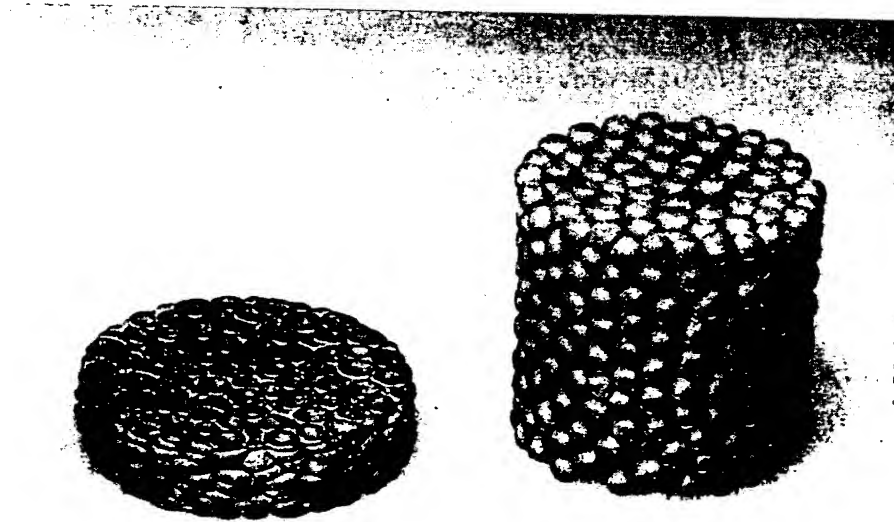


Fig. 31. Open hollow sphere structure made from stainless steel spheres by sintering: after and before axial deformation. Diameter of parts is about 20 mm (source: Fraunhofer).

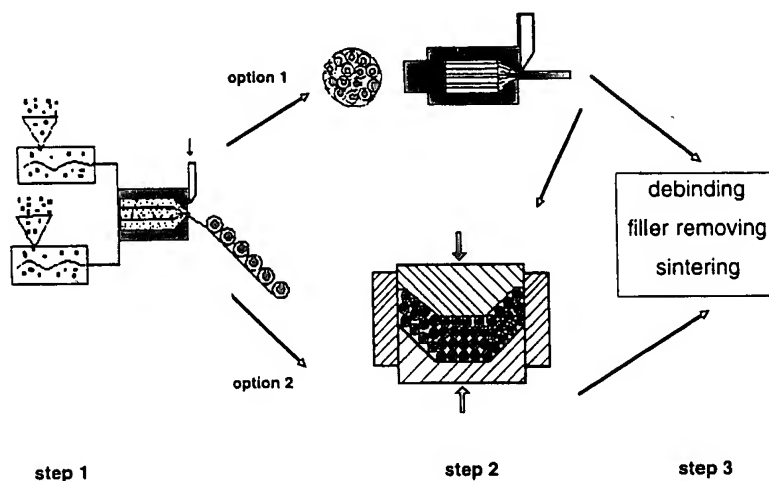


Fig. 32. Process for making cellular metals with oriented porosity from metal powders [230].

creating a bonding not only between the spheres but also between the face sheets and the spheres.

One of the advantages of hollow sphere structures is that the pore size distribution is not random as in the case of the foams described in Sections 2.1.1–2.1.3 but can be tailored by a proper selection of the hollow spheres. The mechanical and other physical properties of hollow sphere structures are therefore more predictable than the properties of “true foams” with a random pore size. A further advantage is that, in principle, the full range of materials available in powder metallurgy can be used for the process, such as superalloys, titanium alloys and intermetallics. Hollow sphere structures can therefore be used in high temperature applications.

Instead of filling the interstices with metal powder, liquid metal can be used for infiltration [217], preferably by applying pressure and pre-heating the spheres to ensure for a complete filling of the structure [224,225]. This creates a direct link to the processes described in Section 2.1.4.

2.2.6. Metal powder/binder methods

Mixtures of metal powders and polymer binders can be pressed or extruded and then heat treated to produce porous materials and components [226–228]. Although no space holding fillers are used, porosities up to 50% have been achieved. In a similar way, materials with oriented pores (baptised “micro-honeycombs”) can be made [229,230] with channel diameters ranging from several microns to several millimetres and based on a variety of metals and alloys. The process steps required are explained in Fig. 32. Bimaterial rods are first prepared which have a core consisting of a mixture of a plastic binder with a volatile space holder and a shell of a metal powder/binder mixture. Next, bundles of such rods are pressed to a green part. This can either be done by extrusion of the bundles, yielding a green part of almost arbitrary cross-section, or by axial pressing to a green part of a complex shape. In a third step,

the binder and the space holder are removed and the metal powder is consolidated by sintering. Fig. 33 shows an example for a micro-honeycomb made of iron.

2.2.7. Reaction sintering

Reaction sintering of metal powder mixtures such as Ti + Al, Fe + Al or Ti + Si is also known to yield porous structures [231–235]. This is due to different diffusion coefficients of the components of a multi-component system in each other.

2.3. Electro-deposition technique

Deposition techniques start from the ionic state of metals, i.e. a solution of ions in an electrolyte [236]. The metal is electrically deposited onto a polymeric foam with open cells which is later removed (see Fig. 34). This process and the investment

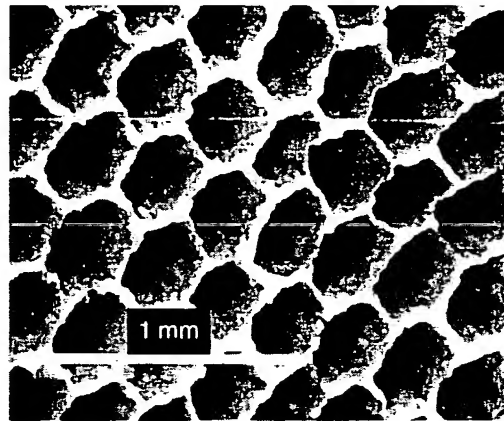


Fig. 33. Porous iron sample with oriented cells of hexagonal cross-section (86% porosity) [230].

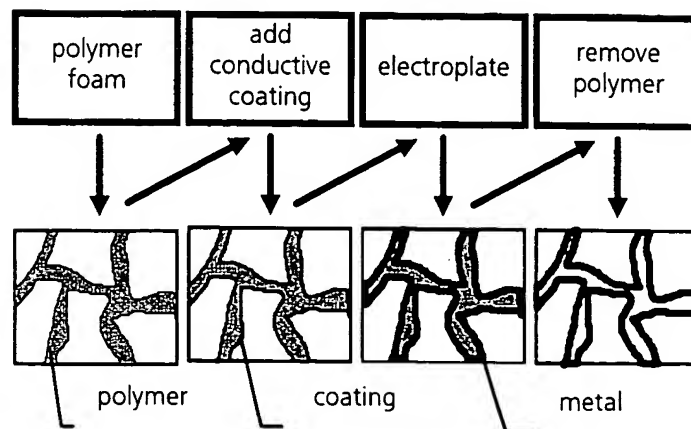


Fig. 34. Electro-deposition technique for making metal foam.

casting route described in Section 2.1.4 therefore share that the actual foaming does not occur in the metallic state. Instead, a foamed polymer is used which is replaced by a metal during processing. Electro-deposition on a polymer foam requires some electrical conductivity of the initial polymer foam. This can be achieved by dipping the polymer foam into an electrically conductive slurry, based on graphite or carbon black, by immersing the foam into an electroless plating solution, or by coating the polymer with a thin conductive layer by cathode sputtering [237,238]. After electroplating the polymer can be removed from the metal/polymer composite by thermal treatment. A three-dimensional arrangement of hollow metallic struts as shown in Fig. 35 is obtained. The inset of the photograph shows that the struts are hollow. Foams of various grades can be fabricated ranging from 2.5 to 30 cells/cm (about 6–70 ppi). The corresponding cell size is from 3.2 to 0.5 mm, the surface areas range from 500 to 7500 m²/m³ [239]. The preferred metals are nickel or nickel–chromium alloys but copper foams can also be made. Nickel–chromium foams are manufactured by making alternate coatings of nickel and chromium, after which a heat treatment creates an alloy by thermally induced interdiffusion of the two metals. Foams have been offered on a commercial basis under the name Retimet (Dunlop, GB), Celmet (Sumitomo Electric, Japan) [239] and Recemat (SEAC, The Netherlands) [240]. Production volumes at Sumitomo are reportedly in the range of hundreds of tons per year. Sheets with thicknesses between 2 and 20 mm are available with densities ranging from 0.4 to 0.65 g/cm³ for nickel or nickel–chromium foams. The density of such foams has been found to be virtually independent of the average pore size [240]. Mechanical properties and some simple models for these materials can be found in Refs. [238,341].

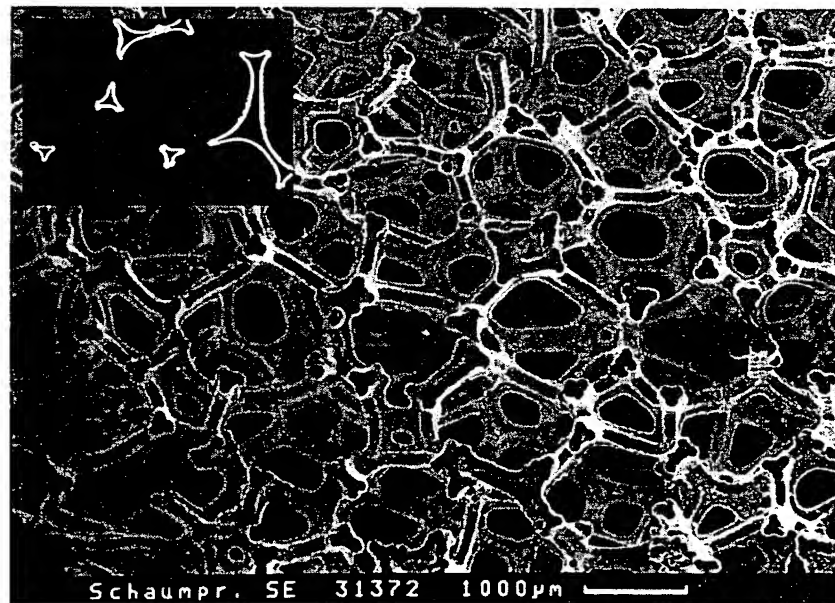


Fig. 35. Nickel foam prepared by electro-deposition. Inset: micrograph of the edges of some of the hollow struts (source: Fraunhofer).

2.4. Vapour deposition

Metal foams can also be made from gaseous metal or gaseous metallic compounds. A solid precursor structure is required which defines the geometry of the foam or cellular material to be produced. As an example, reticulated polyurethane foams or the lattice block polymers precursors mentioned earlier in Section 2.1.4 can be used. Metal vapour in a vacuum chamber can be produced and the vapour allowed to condense on the cold precursor. The condensed metal coats the surface of the polymer precursor and forms a film of a certain thickness characterised by the density of the vapour and the exposure time. One way to carry out this process is by arc vapour deposition [241]. Alternatively, for manufacturing nickel foams one can make use of the very efficient nickel carbonyl route to coat the precursor with nickel at quite low temperatures. Nickel carbonyl is produced by reacting $\text{Ni} + 4\text{CO} \rightarrow \text{Ni}(\text{CO})_4$ [242]. Nickel carbonyl is a gas which decomposes into nickel and carbon monoxide when heated to temperatures above 120°C . One can therefore coat the polymer precursor by letting a stream of nickel carbonyl gas go through it at such temperatures. The nickel formed during decomposition will accumulate on the precursor, thus creating a metallic coating. The polymer can simply be kept at the required decomposition temperature of the carbonyl by using infrared heating [243,244]. After cooling, the polymer can be removed by thermal or chemical treatment and the same kind of material with hollow struts is obtained as in the galvanic process described in Section 2.3 Nickel foams made this way are available commercially under the name “Incofoam” [245] in thin sheets up to 3.3 mm thickness. Densities range from 0.2 to 0.6 g/cm^3 , material purity is very high (99.97% Ni), and tensile strengths are around 0.6 MPa for a medium density. The appearance of “Incofoam” (shown in Fig. 36) is very similar to that of the foams made by electro-deposition (compare with Fig. 35). The main application at the moment is as support material for pasted battery electrodes.

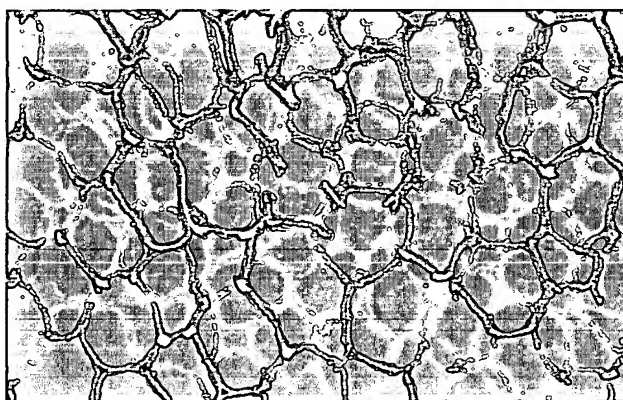


Fig. 36. “Incofoam” sample made via nickel carbonyl process (20 ppi) [245].

2.5. Summary: production methods

Table 2 summarises all the production methods discussed in Section 2. The limits given for the achievable porosity and the metals for which the single processes can be carried out are, of course, subject to constant changes and additions as research continues. Commercial availability does not mean that a material can be bought from stock but that the material may be supplied in a reasonable time on request.

3. Methods for characterising cellular materials

Cellular metals and alloys can be characterised in many ways. The objective is either to obtain mechanical or physical data characteristic of the cellular material investigated or to carry out a technological characterisation of a component containing cellular metal. There are two ways to look at a cellular material: from an atomistic or molecular viewpoint a cellular material is a *construction* consisting of a multitude of struts, membranes or other elements which themselves have the mechanical properties of some bulk metal. Testing a cellular material is therefore equivalent to testing any engineering component. From a macroscopic viewpoint the cellular structure is a *material*, and tests yield properties corresponding to the material. Adopting this viewpoint one looks at the cellular structure as a homogeneous medium which is represented by effective (or averaged) materials parameters.

The various *methods* for the characterisation of cellular metals shall be briefly reviewed in this section. However, no survey of the *results* of such measurements is provided because this is beyond the scope of the present paper. References on the properties of cellular metals manufactured by one of the methods described in Section 2 are given in the corresponding sections describing the materials and also in Table 1.

In general, one can distinguish non-destructive and destructive methods according to whether the foam is irreversibly deformed or otherwise changed, or remains unchanged or only minimally affected during characterisation.

3.1. Non-destructive testing

A wide range of non-destructive methods is available for characterising materials and components [246]. Only these techniques which have been used for investigating cellular metals or for which a possible use for this purpose has been discussed shall be presented in the following sections.

3.1.1. Density measurements

The overall density of a porous material can be determined by weighing it and by measuring its volume using Archimedes' principle, i.e. by measuring its buoyancy in a liquid of given density. If the sample to be characterised does not have a closed outer skin, penetration of liquid into the pores has to be prevented by coating its surface, e.g., with a polymer film.

Table 2
Production processes for cellular metals and metal foams

Category	Section	Process	Achievable porosity (%)	Metals (examples)	Commercially available?
Liquid state processing	2.1.1	Direct foaming by gas injection	80–97.5	Al, Zn	Yes
	2.1.1	Direct foaming with blowing agents	91–93	Al, Zn	Yes
	2.1.2	Gasars	5–75	Ni, Cu, Al, Mg	No
	2.1.3	Powder compact melting	60–90	Al, Zn, Pb	Yes
	2.1.4	Investment casting using polymer foams	80–97	Al, Zn	Yes
	2.1.4	Lattice block materials	–	Al	No
	2.1.4	Casting around space holders	≤65	Al, Zn, Pb, Cu	Yes
	2.1.5	Spray forming	≤60	Steel, Cu	No
	2.2.1	Sintering of powders and fibres	20–80	Bronze, steel	Yes
	2.2.2	Gas entrapment	≤45	Ti	No
Solid state processing	2.2.3	Foaming of slurries	≤93	Al	No
	2.2.4	Powderpressing around space holders	≤70	Ti	No
	2.2.5	Hollow sphere structures	≤80	Steel	No
	2.2.6	Powder/binder techniques	≤50	Fe, Cu	No
	2.2.7	Reaction sintering	92–95	TiAl, FeAl	No
	2.3	Electro-deposition	93–97.5	Ni, Cu	Yes
	2.4	Vapour deposition		Ni, Ni-Cr, Cu	Yes

3.1.2. Dye penetration measurements

The liquid foaming methods described in Section 2.1 yield foams with closed cells or even a closed outer skin. However, in practice imperfections occur while making the foams, e.g., in the cooling stage after foaming. Such imperfections can include little holes or cracks in the cell walls or in their outer skin. Penetrant techniques are ideal for detecting such surface defects [246]. For this a liquid chemical is first applied to the foam to be investigated. The chemical is eventually absorbed by the holes and cracks. After drying the surface, a colouring developer is applied which creates colour where the penetrant chemical has been retained. In this way, maps of the imperfections can be obtained in a simple visual manner [247].

3.1.3. X-ray radiography and radioscopy

Cellular metals can be mapped by simple X-ray absorption techniques (transmission radiography). An X-ray beam is directed through a sample and its attenuation is measured. One averages over a certain lateral area and scans over two dimensions, thus obtaining a 2D absorption map of the foam. The method yields an integrated signal along the direction of the beam, i.e. the attenuation is related to the total mass in a column of material. If thin slices of foam are investigated, i.e. pieces with a thickness in the order of the average pore diameter one can resolve individual pores and map the true pore morphology. However, if the slices are much thicker, single pores are not further distinguishable. Even features such as big pores or holes of a size of one fourth of the thickness of the foam cannot be resolved properly in some cases [247]. Fig. 37 shows an inhomogeneous lead foam in transmission. Some of the very large pores can be seen, but it is impossible to resolve most of the small pores because many pore images are superimposed on each other. For thin slices of foam or foams with low densities, however, the situation is more favourable. Recently the evolution of metal foams which were 4–10 mm thick could be observed in real time by using synchrotron radioscopy [343]. Up to 3 images with 40 μm resolution were obtained per second and, e.g., individual cell walls could be observed as they ruptured. The densification behaviour of aluminium foams has been monitored by measuring X-ray absorption perpendicular to the force [250] allowing for the direct observation of deformation bands.

3.1.4. X-ray computed tomography

Three-dimensional density distributions can be obtained by means of computed X-ray tomography (CT) [251,342]. X-ray images of a sample are taken from a large number of directions, usually by rotating and translating the source and the detector around the sample (spiral scanning, see Fig. 38). From the various images obtained the attenuation of the rays at any point of the object and therefore the local density are reconstructed mathematically [46]. Fig. 39 shows a high resolution image of a zinc foam obtained by this method. The sample shown is about $5 \times 5 \times 5 \text{ mm}^3$ large, spatial resolution is 5 μm . A synchrotron generated X-ray beam (52 keV) was used for obtaining this image which even resolves the internal surface structure of the cell walls. Usual medical or technical tomographs are obviously much more limited in resolution yielding about 0.7 or 0.1 mm, respectively. This lower resolu-

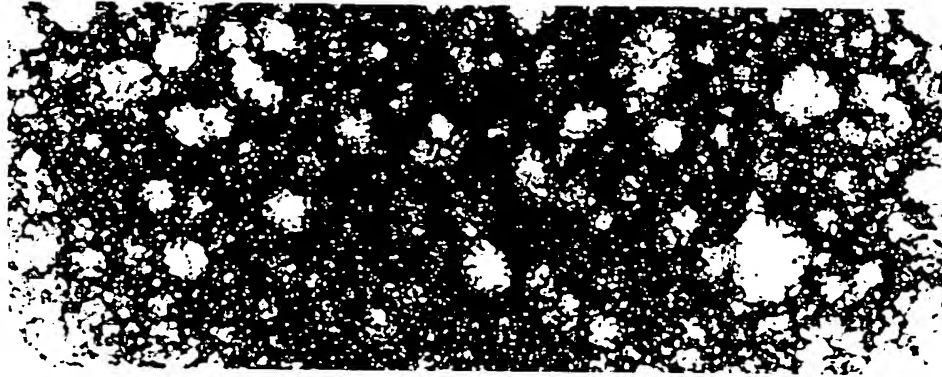


Fig. 37. Image of a lead foam obtained by X-ray transmission radiography. Samples (6 mm thick) contained large pores due to agglomeration of blowing agent in the precursor (see Section 2.1.3). Image shown covers an area of about $60 \times 20 \text{ mm}^2$ (source: Fraunhofer).

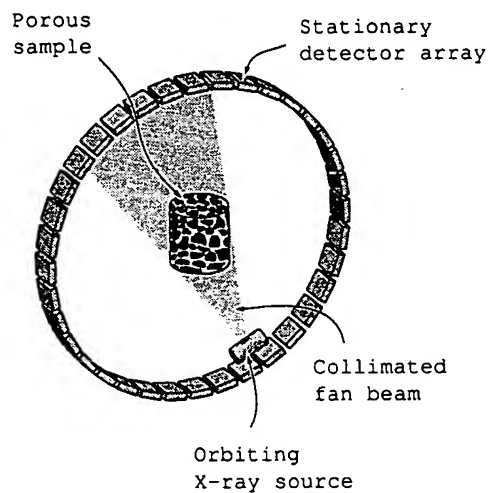


Fig. 38. Experimental set-up in X-ray computed tomography [46].

tion, however, is sufficient for quality control of cellular components in most cases because for obtaining 3D density distributions the CT raw data is averaged over rather large 3D volume elements anyway. The choice of the size of these elements depends on the information desired. If one wants merely to detect hard and soft regions in the foam, the averaging volume is of the order of an average cell volume, i.e. in the range of millimetres [247].

A comparison of 2D and 3D techniques is given in Refs. [252,253]. Computed tomography was used to visualise the deformation bands in aluminium foam by taking a series of CT images in various stages of deformation of one sample and by constructing 3D displacement maps from pairs of images in analogy to the surface displacement technique already described [249].

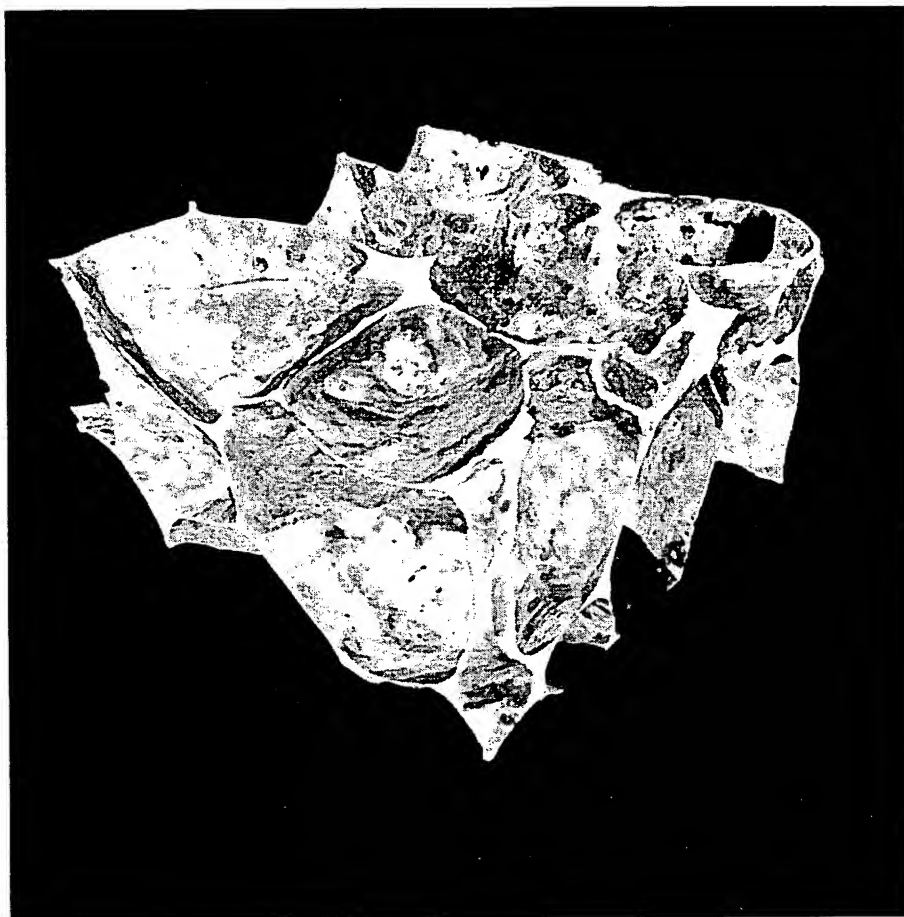


Fig. 39. High resolution 3D-image of a zinc foam obtained by computed tomography. Sample dimensions are about $5 \times 5 \times 5 \text{ mm}^3$ (source: L. Helfen and T. Baumbach, ESRF Grenoble).

Nuclear magnetic resonance tomography, a valuable tool in scanning human bodies, is not suited for investigating metallic structures because the penetration depth of the stimulating rf field is very small for the frequencies usually applied (for aluminium, 11 MHz \times magnetic induction of field in tesla).

3.1.5. Eddy-current sensing

Foams can be characterised by their relative density and pore size by carrying out multifrequency electrical impedance measurements [255]. This is achieved by using an excitation coil that produces an alternating magnetic field. Induction causes eddy currents and a corresponding magnetic field around the metal foam sample, which can then be picked up with a secondary coil. The eddy currents not only depend on some geometrical factors and frequency, but also on foam properties. It can be shown that porosity has a marked effect on the output signal. Therefore, this

method can be used to measure local densities and other pore parameters in a sample after appropriate calibration.

3.1.6. Acoustic measurements

The sound absorption properties of porous media are usually measured in an impedance tube, which allows for quick and precise measurements. However, as only perpendicular incidence of the sound wave on a sample can be characterised, further tests have to be carried out before a newly developed sound absorber can be used. The impedance tube contains the disk-shaped sample near one end with a variable distance to the rear wall and a sound emitter and detector at the opposite end [256]. For the usual acoustic frequency range tubes of about 60 cm length and 30 or 100 mm diameter are used for high (≈ 0.8) kHz, and low frequencies (≈ 1.6 kHz), respectively. Normally one measures the attenuation as a function of frequency. If the cavity between sample and rear wall is also varied, one obtains a series of functions $\alpha(\nu)$, absorption coefficient versus frequency. If the samples have interconnected pores, the absorption curves are shifted to lower frequencies when the cavity is enlarged. Dense samples and porous samples with closed pores, however, have the same absorption curve independent of the cavity because sound cannot penetrate the sample and the absorption takes place on its surface. It is necessary to carry out measurements on more than one sample, particularly for small tube diameters, and it is useful to make two measurements for each sample, each one for one possible orientation of its sides. The surface dominated absorption of closed cell foams is clearly different for the two orientations, whereas the volume dominated absorption of open structures remains unchanged when the sample is flipped.

3.1.7. Vibrational analysis

Young's modulus and the loss factor of materials can be determined by vibrational analysis. In the simplest technique, a long bar of rectangular or round cross-section or a thin quadratic plate made of the material is forced into vibrations. Longitudinal, transverse or torsional excitations can be created. The sample can be clamped at one or two ends, or be supported by or suspended from thin wires. The sample can be excited by magnetic fields and the resulting vibrations can be picked up by an impedance coil. Another possibility is to fix the sample directly to an electromagnetic shaker to avoid clamping [257]. The amplitude of vibrations as a function of excitation frequency shows characteristic resonance peaks. The positions of the peaks ν_p allow one to calculate Young's modulus E from the sample dimensions and mass using standard formulae. The widths $\Delta\nu/\nu_p$ of the resonance peaks define the loss factor η [258]. Measuring the properties of cellular materials, however, is not trivial. The materials are often inhomogeneous with an unknown mass distribution. The effective (average) Young's modulus obtained from the resonance frequencies for such an inhomogeneous material then depends on the mass distribution. In measuring the loss factor, one has to suppress the influence of parasitic losses from the sample support. Using clamps, one introduces friction between clamps and samples, whereas supporting a foam bar on thin wires creates problems because the location of the vibrational nodes of the inhomogeneous sample is unknown [151].

3.1.8. Porosimetry and permeametry

Dealing with cellular metallic materials with open pores one is interested in determining parameters related to the internal structure: specific surface area, pore size distributions and channel size distributions. Various methods are currently in use:

Mercury porosimetry. It is based on the intrusion and extrusion of mercury into the pore volume under pressure. The intruded volume and pressure data are related to the size of the cells. However, pores larger than a few hundred microns are hard to detect.

Gas absorption techniques (BET). They allow for a fairly accurate determination of the total internal surface area of a cellular material. Even very small pores down to an atomic scale can be detected.

Permeametry. It is based on the study of a gas or liquid flow through a porous medium. One measures the pressure drop Δp along a foam column of height s as a function of mean fluid velocity v and finds a linear relationship for very slow flow (Darcy's law for flows dominated by viscous forces) and a quadratic dependence for higher flow rates (Forchheimer law) when energy losses due to the inertia of the flowing fluid become important. Some results for a gas flow through various open-cell aluminium samples are shown in Fig. 40. By knowing the viscosity of the fluid, a permeability and a friction coefficient can be derived. Assuming that the friction is related to the internal surface area of the pore volume, an estimate can be obtained for the specific surface area. The values obtained this way are lower than the ones from BET measurements because only a part of the internal surface interacts with the flowing fluid [259].

Bubble point method. With this technique, the pore volume is first filled with a fluid. A monotonously increasing external pressure is then applied. At a certain pressure value, the capillary force of the liquid is overcome and the liquid is blown out of the test specimen giving rise to a resistance drop. By further increasing the

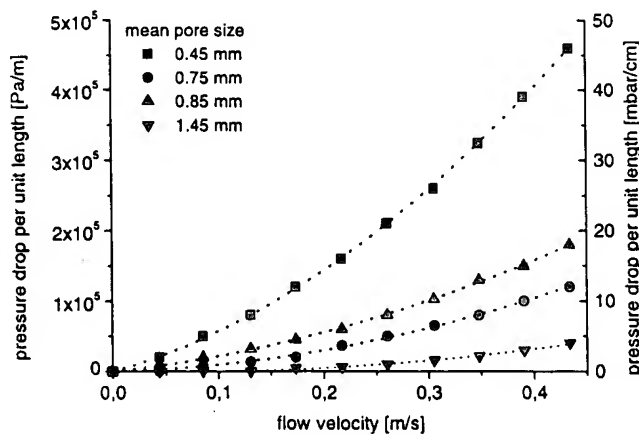


Fig. 40. Pressure drop measurements on various open-cell materials (as shown in Fig. 22) [184].

applied pressure, one can empty increasingly smaller pores until finally the sample is dry. By comparing the flow rate as a function of the pressure drop with the corresponding curve of a dry sample, the largest through-pore of the specimen and some information about the pore size (or better the channel size) distribution can be determined.

3.1.9. *Electrical and thermal conductivity measurements*

Measurements of the electrical resistivity are fairly straightforward. Owing to the low resistivity of metallic materials a small cross-section is desirable. However, the finite cell size imposes a minimum on the cross-section. A good contact between the leads and the foam has to be ensured. For aluminium foams, with average pore diameters of about 2 mm, rectangular specimens with a cross-section of 200 mm² and 200 mm length have been used. The measurements were carried out in the four-point mode with copper contact plates clamped to the foam [132].

Thermal conductivities have been measured following a modified standard procedure on samples of aluminium foam with a cross-section of 20 × 20 mm [50].

3.1.10. *Other methods*

Other methods could be used for characterising cellular metals, although some of them have never been tried and, until now, there is no proof that they can be useful.

3.1.10.1. *X-ray and neutron small angle scattering.* Small angle scattering can be used to measure pore size distributions in cellular systems. A collimated beam of monoenergetic X-rays or neutrons is directed on the sample and scattered under small angles. The scattered intensity I is plotted as a function of the scattering wave vector q [260]. The scattering function $I(q)$ depends on the internal structure of the sample. A metal with a random distribution of spherical pores of equal size will create a characteristic function. Assuming such a simple model one can derive the pore radius or the pore size distribution [344]. X-rays allow for the exploration of nanometre sized pores, whereas neutrons can give access to the investigation of much coarser pores with diameters up to a few tens of micrometres. In any case these methods can only be applied to microporous metallic systems.

3.1.10.2. *Diffusive wave spectroscopy.* The use of acoustic diffusive wave spectroscopy was proposed for the investigation of metallic foams [261]. The optical counterpart of this method was successfully applied to liquid aqueous foams [262]. Small changes in foam structure, e.g., after small mechanical deformations, could be detected by this method.

3.1.10.3. *Ultrasound imaging.* A possible method for obtaining images of the internal structure of cellular materials is by ultrasound imaging. No successful experiments of this kind are currently known [247]. However, the use of ultrasound imaging for characterising the structure of liquid aqueous foams at least in a qualitative manner seems to be realistic [263] giving rise to some hope that the same could be done for metallic foams.

3.2. Destructive testing

3.2.1. Optical image analysis

The cell morphology and microstructure of cellular metals can be analysed by optical observations at various magnifications. Although the actual analysis is non-destructive, sample preparation usually requires cutting, embedding or polishing of the materials and is therefore effectively a destructive technique.

One can determine cell or pore size distributions or perform a shape analysis of the cells by using commercial image analysis programmes. These programmes identify the individual cells in the preparation plane. Meaningful results, however, are quite difficult to obtain. A very careful preparation of the materials is required. Cell membranes and the interior of the cells must appear in different brightnesses. One way is to embed the cellular material in a black resin and to polish the preparation plane. Images such as the ones shown in Fig. 41 are obtained. Some manual correction work is usually necessary to help the programme in identifying individual pores and calculating the distribution of pore sizes. Of course, the pore sizes measured in this way are not the true ones because the intersections through the individual cells are randomly oriented in space. Therefore, the results require some interpretation.

Deformation processes of metal foams have been investigated with a method called “surface deformation analysis”. A block of foam is deformed while the outer surfaces of the sample are constantly observed with a video camera. A correlation analysis between image pairs is then carried out from which a surface displacement vector field is derived [248,249,254,327]. This way, the deformation bands occurring when a foam collapses are clearly identified (Fig. 42).

3.2.2. Mechanical testing

Mechanical testing of cellular metals is the prerequisite for any structural application. Mechanical data is either needed for the evaluation of specific applications or more generally to build databases which are needed for computer aided modelling of cellular materials or components containing such materials. The characterisation methods are, in principle, the same as for other non-cellular materials. However, sometimes some modifications of the test procedures are necessary to account for the specific nature of cellular materials. One such speciality concerns statistics: if a metal foam of a given alloy were tested, the resulting mechanical properties of a number of samples with the same overall foam density would show a much larger scatter than usually found in testing conventional materials. The reason for this are “hidden parameters” such as mass distribution, heterogeneous microstructure, etc. which distinguish various samples of the same overall density from each other. Therefore, in order to obtain meaningful results and to average out the hidden parameters, a larger number of samples may be necessary compared to what is required by the testing standards for non-cellular materials. Moreover, as in cellular materials the length scale for macroscopic heterogeneities is sometimes in the range of millimetres, the sample dimensions in mechanical tests might have to be enlarged compared to existing standards [328].

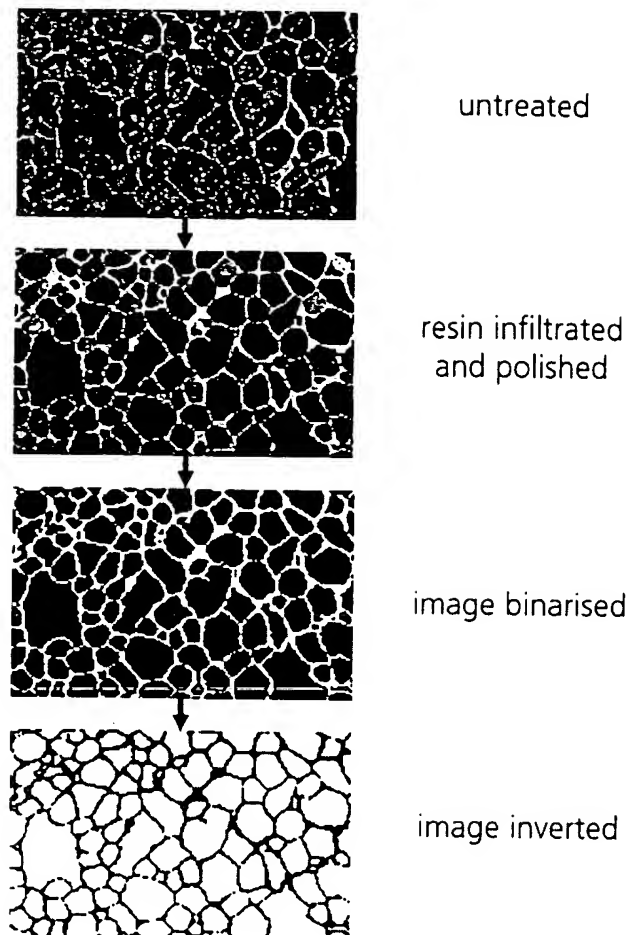


Fig. 41. Optical image analysis of aluminium foams: various stages of sample preparation and image processing are shown [50].

The various different mechanical tests can be labelled by one of the following attributes:

Type of applied stress: uniaxial, biaxial, multiaxial, hydrostatic. Uniaxial tests have been the standard in most experimental work on mechanical properties of cellular metals until now. It has been only just recently that multi-axial tests have been carried out: two perpendicular compression axes in Ref. [51], one compression axis combined with hydrostatic compression in Ref. [71].

Mode of loading: compression, tension, shear, bending, torsion. Compression tests are the ones most frequently carried out because simple cuboid specimens can be used for the tests and clamping of the sample is not necessary. Tension tests have been performed with both cuboid and dogbone-shaped samples. Shear tests require one or two flat sheets of cellular metal attached to two or three steel plates. Bending tests can be carried out in three- or four point configuration. A careful selection of

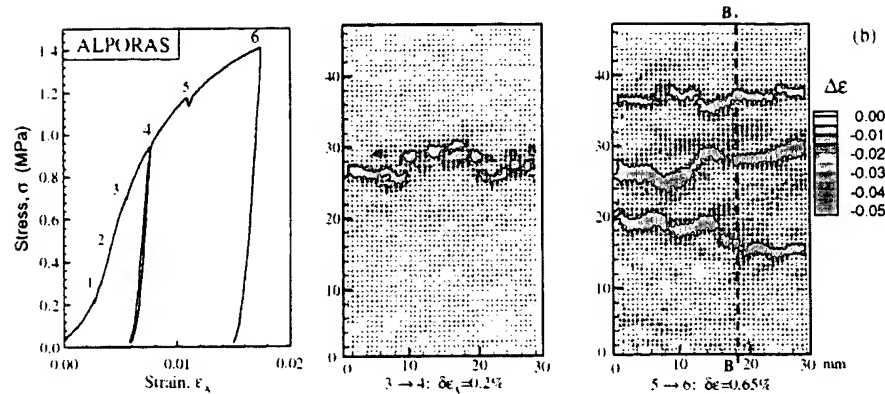


Fig. 42. Deformation behaviour of a metal foam monitored by surface deformation analysis [254]. The darker areas represent the largest deformations $\Delta\epsilon$ (direction of force was from top to bottom).

the supporting and force transmitting rolls are important because local indentations can render the test results useless. Testing foams with closed outer skins one has to take into account that they significantly affect the test results.

Time dependence of load: constant, slowly increasing (quasi-static, $\dot{\epsilon} \approx 10^{-3} \text{ s}^{-1}$), dynamic, cyclic. Most of the work found in the literature was obtained under quasi-static conditions. High strain rates can be realised in drop weight tests (up to 100 s^{-1}), with a split Hopkinson pressure bar (up to $5 \times 10^3 \text{ s}^{-1}$) [158,157] or in ballistic tests (up to 10^5 s^{-1}) [158]. Fatigue tests are most easily carried out in a compression–compression mode for the same reasons which apply to quasi-static tests, but compression–tension, tension–tension and cyclic bending tests have also been performed by preparing and fixing appropriate samples. If failure is in compression, the problem is to identify the point of failure. One can define a critical strain as a failure criterion [160] or the knee of the strain versus cycles curve [52]. Creep tests are carried out under given constant loads.

Other mechanical tests include fracture toughness measurements on notched samples and indentation tests with various indenter shapes [345]. For sandwich panels with a cellular core, there are technological tests to describe the bonding between the face sheets and the core, such as the drum peel test (ASTM D1781). Mechanical deformation processes in metallic foams can be monitored by recording the acoustic emissions by the breaking cell walls [346], a technique which can be complementary to ordinary strain measurements.

3.2.3. Corrosion testing

There are no established corrosion test standards for cellular metals until now. One usually applies test standards established for other purposes, e.g. for testing automotive components. Sandwich panels with an aluminium foam core were characterised in a test programme consisting of 10 cycles of 7 days which in turn contained 24 h of exposure to salt spray, $4 \times 24 \text{ h}$ of variable humidity and 48 h at room temperature and normal humidity (23°C, 50%) [50].

4. Applications of cellular metallic materials

4.1. General considerations

Cellular metallic materials are finding an increasing range of applications. Whether a suitable porous metal or metal foam can be found to solve a given problem depends on many conditions, summarised here by the following keywords:

- (i) *Morphology*: type of porosity needed (open versus closed), amount of porosity needed, size scale of porosity desired, total internal surface area of cellular material required;
- (ii) *Metallurgy*: metal or alloy or microstructural state required;
- (iii) *Processing*: possibilities for shaping the foam or cellular solid or for manufacturing composites between the foam and conventional sheets or profiles;
- (iv) *Economy*: cost issues, suitability for large volume production.

The first point, in particular, is crucial for any evaluation of cellular metallic material applications. Many applications require that a medium, either liquid or gaseous, be able to pass through the cellular material. There may be a need for various degrees of “openness”, ranging from “very open” for high rate fluid flow to “completely closed” for load-bearing structural applications, and appropriate materials satisfying these conditions have to be found. Fig. 43 shows what types of porosity the various application fields (to be discussed in detail in the following sections) require. Normally, a difference is made whether an application is “functional” or “structural”, the difference between these two notions, however, being rather gradual.

The question from which metals or alloys a given type of cellular structure can be manufactured is also important. Structural, load bearing parts have to be light because otherwise they would be made from conventional massive metals or alloys.

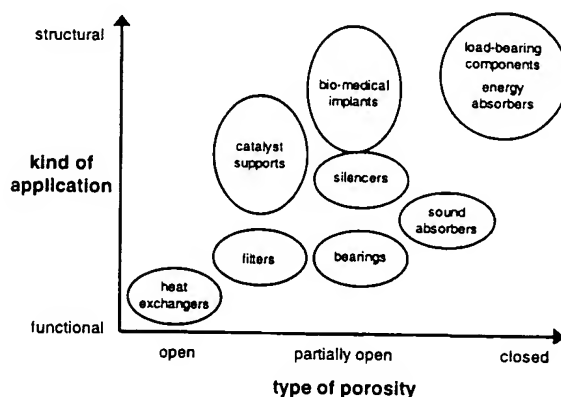


Fig. 43. Applications of cellular metals grouped according to the degree of “openness” needed and whether the application is more functional or structural.

Therefore, aluminium, magnesium or titanium foams or porous metals are preferred for such applications. For medical applications, titanium may be preferred because of its compatibility with tissue. Stainless steel or titanium is required for applications where aggressive media are involved or high temperatures occur.

Finally, processing and cost issues have to be considered [347,348]. The technology must be available to bring the selected cellular metal into the required shape and to incorporate it into a machine or vehicle where it has its function. A technology for making cellular metal will be futile if the required component cannot be manufactured at a reasonable price.

In the following two sections, applications for cellular metals are discussed. In many cases, application concepts are presented which are still in the phase of verification. In the next section, predominantly, structural applications are presented (mostly with closed cell foams). After this, functional applications requiring materials with open porosity are discussed.

4.2. Structural applications of metal foams in various industrial sectors

4.2.1. Automotive industry

The increasing demand for safety of automobiles has lead to a higher vehicle weight in many cases. This conflicts with further demands for low fuel consumption, necessitating additional measures for weight reduction. Moreover, especially in Europe and Japan, cars with reduced lengths are desired. This reduction, however, should not take place at the expense of the size of the passenger compartment. One therefore tries to introduce new compact engines or reduce other structures to maintain passenger comfort. This creates new problems with heat dissipation in the engine compartment, because all aggregates are very closely spaced, or with crash safety owing to the reduced length of the crash zones. Finally, the need to reduce acoustic emissions from cars has led to a demand for new sound absorbers.

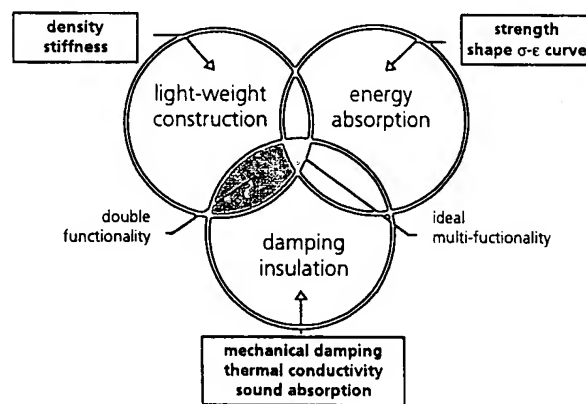


Fig. 44. Main automotive application fields of structural metal foams.

Metal foams offer a possible solution for some of these problems. Fig. 44 summarises the three application fields for metal foams, mostly aluminium foams, in the automotive industry. The inner circles represent the three fields which have to be distinguished and the outer boxes illustrate the foam properties which are responsible for the advantage in the given field. An ideal application would be a part which served as a light-weight panel, absorbed energy in crash situations and carried sound or heat absorbing functions (intersection of the three circles in Fig. 44). Such multi-functional applications are, of course, difficult to find and one often would be satisfied with finding a two-fold application where, e.g., a structural light-weight panel served as a sound absorber at the same time.

4.2.1.1. Light-weight construction. Light-weight construction depends on two properties of metallic foams: they exhibit a range of almost reversible, quasi-elastic deformation and their stiffness-to-mass ratio is high. The latter property can easily be understood by considering an example: the stiffness of a flat panel is proportional to Eh^3 , where E is Young's modulus of the panel material and h is the panel thickness. Suppose that various panels are made of foamed materials of various densities but all have the same weight per unit area. E is roughly proportional to the square of the density of the foam ρ , while of course $h \propto \rho^{-1}$. Therefore, the stiffness of a flat panel of a given weight is proportional to ρ^{-1} , which means that foams with, e.g., one fifth of the bulk density of a metal, have stiffness-to-mass ratios which are five times higher than that of conventional sheets of the same weight. The assumed quadratic density dependence of E reflects most empirical observations on imperfect foams. For a perfect foam with closed cells, a linear dependence $E \propto \rho$ would be expected. If better foams with less imperfections could be made, even higher moduli could therefore be expected [264] and the gain in stiffness by using such panels would be even higher.

For sandwich panels, the weight advantage is even larger than for plain foam sheets and a suitable design optimisation must be carried out to determine the ideal thickness of the face sheets and the most suited density of the foam core [1,10,265].

The consideration of minimum weight structures with an optimum stiffness, however, is more complicated than suggested by this simple comparison of foamed and dense sheet material. In reality, foam-based structures have to compete with conventional structures with optimised mass distributions, i.e., aluminium foams have to be compared with aluminium extrusions, aluminium foam sandwiches with aluminium honeycombs or waffle-stiffened panels. It has been shown that such structures can perform as well or better than foams [10,264,266]. Foam-based structures nevertheless can be preferable for some reasons:

- (i) they may be easier to manufacture in a given complicated geometry (and therefore may be cheaper). Honeycombs outperform flat foam panels for stiffness per weight but 3D-shaped honeycombs are very difficult and expensive to manufacture in contrast to foamed sandwich panels;
- (ii) foam-based structures may be more robust and damage tolerant, and the failure behaviour less catastrophic;

- (iii) metallic foams may exhibit additional properties which are useful, e.g. heat resistance or acoustic properties.

Light, stiff structures made of aluminium foam — preferably in the form of sandwich panels — could therefore help to reduce weight in cars. Examples are bonnets, boot lids and sliding roofs, where a high stiffness is needed in order to avoid torsional deformation or to prevent these parts from vibrating. In a design study carried out by DaimlerChrysler, a rear intermediate panel was made of aluminium foam (density 0.6 g/cm^3 , no face sheets) and compared to a magnesium high pressure die-cast part. It was found that the torsional stiffness was about the same in both cases at nearly the same weight [267]. The German manufacturer Karmann (Osnabrück) is currently testing three-dimensionally shaped sandwich panels in convertible and racing cars where stiffness and weight problems are serious. Two aluminium foam sandwich parts, one for the front bulkhead and one for the rear wall, replace the conventional components made of stamped steel sheets, thus not only reducing the weight by 25% but also increasing stiffness by 700% in one case [125,126]. Because aluminium foam sandwich parts are more expensive than conventional stamped steel sheets, such an application would not be viable in spite of the weight reduction achieved if it only were a simple substitution of materials. However, by using very stiff sandwich structures for conventional sheets, one can introduce new constructional principles for the body frame of the vehicle. A consequence is that the number of components needed in the car can be significantly reduced if one applies the aluminium sandwich technology, hence decreasing construction costs.

4.2.1.2. Crash energy absorption. In energy absorption applications, one exploits the plastic, irreversible deformation regime of materials. Many cellular solids are excellent energy absorbers owing to their deformation at a nearly constant stress level over a wide range of strain [1]. Metal foams might outperform conventional foams, e.g. polymer foams, because of their much higher strengths. What makes aluminium foams even more attractive is their low rebound in dynamic crash situations which has been determined to less than 3% in one study compared with 15% for a polyurethane foam [91]. Therefore, an important application field for cellular metals in general and metallic foams in particular is energy absorption.

Passive safety regulations for vehicles require that the collision energy is dissipated in designated areas and the rigid passenger cell is protected. One distinguishes various impact velocity ranges. In the low velocity regime (≤ 3 to $\leq 10 \text{ km/h}$ depending on the manufacturer), the energy is absorbed reversibly by elastic materials or hydraulic impact dampers. In the intermediate regime (up to 20 km/h), a controlled, programmed deformation of certain designated crash elements (“crash boxes”) is included [268]. Such elements can be simple circular aluminium tubes. These elements are fairly easy to replace after crashes making repairs affordable. Only in the high velocity regime is the chassis deformed irreversibly leading to severe vehicle damage. Various crash situations may be distinguished such as head-on impacts, side impacts, oblique impacts, roll-over situations, etc. [269]. For each situation, an

energy absorber has to perform in a different way but some general criteria for a good energy absorber can be mentioned here:

- (i) energy absorption characteristics as ideal as possible. Normally, one requires a rectangular stress–strain behaviour, i.e. yielding only after the maximum tolerable stress has been reached and progressive deformation at this plateau stress;
- (ii) a high absorption capacity per volume, length or mass unit;
- (iii) isotropy of energy absorption, i.e. good absorption characteristics for at least a wide range of impact directions.

Homogeneous aluminium foams or syntactic cellular metals show quite good absorption properties: they exhibit a fairly long plateau range, although a certain unwanted residual slope of the stress–strain curve is often observed [269]. Moreover, the energy absorption is quite isotropic [154] except for some cases where the manufacturing route creates anisotropies. However, most application studies concentrate on cellular metals having some dense outer skin or face sheets surrounding the cellular core. The reason for this is that apart from advantages of improved corrosion protection, such composite structures can have even better energy absorption characteristics than bare foams. The influence of the interaction between foam and outer skins can be seen in Fig. 45 where the compression of two aluminium foams is compared. One foam has densified outer skins parallel to the force, whereas the other foam does not. It is apparent that the outer skins lead to a better plateau behaviour and higher plateau stresses, although the corresponding sample has a lower density. The effect can be even more pronounced if foam filled sections are compared with empty sections [53,54,154]. A foam filling significantly changes the deformation behaviour and failure mode of hollow sections and can therefore lead to additional absorption effects and weight savings. On the other hand, use of sections introduces some anisotropy. If one considers sections one has to distinguish between axial [53,54,154,166,167,268,270–276] and bending [165,276] behaviour.

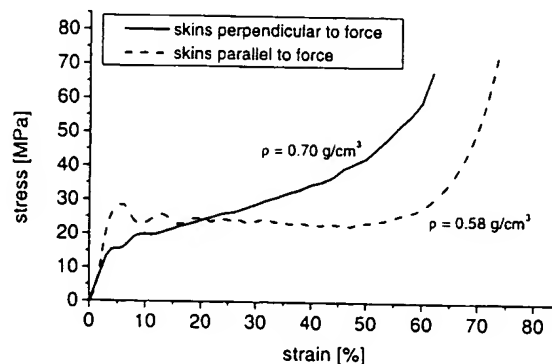


Fig. 45. Comparison of the stress-strain behaviour of foams where the outer skins are oriented in different directions relative to the applied force [154].

Examples of applications where foam-filled structures are crushed axially include crash boxes for head-on impacts or underride protectors for lorries, whereas crashing in the bending mode is involved in A- or B-pillar reinforcements or in other side impact protections.

4.2.1.3. Noise control. Polymer foams are often used for noise control. It is therefore near at hand to evaluate metal foams for their potential use [278]. There are various ways in which aluminium foams could help reduce noise and care must be taken not to confuse the various ways of action. First of all, there is the problem of undesirable vibrations of a construction (machine, vehicle, etc.) which can cause damage and lead to the emission of sound waves (noise). As Young's modulus of metal foams is lower compared to the corresponding ordinary bulk metal, the resonance frequency of a metal foam structure will generally be shifted to lower frequencies in comparison to a conventional construction. Also, the loss factor of foams is higher than the loss factor of the ordinary metal by a factor of at least 10 so that vibrations will be damped out — i.e. converted to heat — more efficiently [151–153]. Therefore, foams offer the possibility of avoiding noise problems, although it is worth noting that the loss factor of metal foams is still much lower than that of most polymers.

Sometimes, however, the task is to attenuate an incident or evanescent sound wave. Passengers have to be protected from noise coming from external sources or sound emissions from noisy machines (e.g. cars) must be prevented from propagating freely out into the environment. A sound wave which falls onto a porous material is partially reflected and partially enters the structure. A part of the entering wave is absorbed while the remaining wave is transmitted. Also, resonant vibrations can be created. The reflected wave is attenuated by destructive interference whenever the surface of the foam is not completely closed. However, if the average cell depth is in the range of millimetres, this mechanism will be effective only for rather high frequencies (of the order of ≈ 300 kHz). The sound which enters into the structure is attenuated inside the foam, especially if the pores are interconnected by small channels. The sound wave presses air through these channels numerous times per second. As the air flows through the channels, friction between air and cell walls and turbulent flow dissipate energy. With all mechanisms acting, metal foams can reach quite high absorption levels up to 99% for certain frequencies (usually in the range of 1–5 kHz). An air gap between foam and a fixed wall behind the foam causes a shift to lower frequencies if the cell structure is open.

Sound absorption and insulation is a very important topic in the automotive industry. A problem often encountered is that sound absorbing elements have to be heat resistant and self-supporting. Combinations of polymer foams and aluminium foils might be a solution but are often not desirable. Aluminium foams at the current state-of-the-art technology do not exhibit excellent sound absorption properties due to their predominantly closed porosity but are at least heat resistant and self-supporting. Provided that one could sufficiently improve the sound absorption properties, an excellent material for such heat resistant sound absorbers could be obtained.

“Alporas” foams (see Section 2.1.1) are being used as sound absorbers along motorways and other busy roads in Japan to reduce traffic noise and in the Shin-kansen railway tunnel to attenuate sonic shock waves [67]. For this purpose, foamed sheets are rolled after foaming and slicing [65]. The resulting reduction in thickness from 10 to 9 mm creates a sufficient amount of cracks and other defects in the cell walls to improve sound absorption substantially, although it is still not comparable to established sound absorbing materials (based on polymer foam or glass wool) [66]. However, the combination of the given sound absorption properties with other characteristics such as fire resistance, resistance to weathering, non-generation of dangerous gases in the case of fires and the reported unproblematic cleaning of the foam panels makes “Alporas” a suitable material. Foam panels have also been used for indoor sound absorption purposes in entrance halls of public buildings. Also, the interesting visual appearance of the metal foam is likely an important aspect for some of these applications.

4.2.2. *Aerospace industry*

The light-weight constructional aspect of foamed metals is very similar in the aerospace and automotive sector. In aerospace applications, the replacement of expensive honeycomb structures by foamed aluminium sheets or metal foam sandwich panels could lead to higher performance at reduced costs. On one hand, a higher buckling and crippling resistance is sought [206], whereas on the other hand, an important advantage of foams is the isotropy of the mechanical properties of panels (with or without face sheets) and the possibility for making composite structures without adhesive bonding. The latter gives rise to a more benign behaviour in the case of fires where it is essential that the structure maintains its integrity as long as possible. Boeing (USA) has evaluated the use of large titanium foam sandwich parts made by the gas entrapment technique (see Section 2.2.2 and Fig. 27) and aluminium sandwiches with aluminium foam cores for tailbooms of helicopters. An important advantage of such sandwiches is that they can be fabricated with curvatures and even into 3D shapes in contrast to generally flat honeycomb structures. For this reason, helicopter manufacturers are trying to use aluminium foam parts to replace some of the honeycomb components currently used.

Further applications include structural parts in turbines where the enhanced stiffness in conjunction with increased damping is valuable. Seals between the various stages of the engine are also made of porous metals. The turbine blade cuts the desired contour into the cellular material during its first operation and creates an almost gas-tight seal this way.

In space technology, aluminium foam has been evaluated for its use as an energy absorbing crash element for space vehicle landing pads and as reinforcement for load bearing structures in satellites, replacing materials which cause problems in the adverse environmental conditions in space (temperature changes, vacuum, etc.). For space applications, the use of highly reactive but very light alloy foams such as Li–Mg foams has been considered [279,280]. These alloys, usually not applicable because of their high reactivity, could be useful in a vacuum environment.

4.2.3. Ship building

Light-weight construction has gained importance in ship-building. Modern passenger ships can be entirely built from aluminium extrusions, aluminium sheets and aluminium honeycomb structures. Large panels of aluminium foam with aluminium cores promise to be an important element in some of these structures. If the face sheets are bonded to the core material with highly elastic polyurethane adhesives, one obtains light and stiff structures with an excellent damping behaviour, even at the low frequencies experienced in ships. For applications in ship building, it is important that one can join foam sandwich elements in an effective way and introduce suitable fastening elements during ship construction [281]. Naval applications for cellular materials have also been identified including elevator platforms, structural bulkheads, antenna platforms and pyrotechnic lockers [282].

4.2.4. Railway industry

The application of metal foams in railway equipment follows the same rules as for automotive industry concerning the three main application fields. Energy absorption is an issue especially for light railway sets and trams which operate in urban areas and for which collisions with cars might occur. Japanese trains have been equipped with a 2.3 m³ block of “Alporas” foam to improve crash energy absorption [77]. The advantages of foamed light-weight elements are the same as for cars, the main difference being that structures for railway wagons are much larger.

4.2.5. Building industry

There is a wide range of possible applications in the building industry. As modern office buildings are made of concrete, their facades are decorated with panels which hide the concrete and improve the appearance of the building. These panels have to be light, stiff and fire resistant. Quite frequently thin slices of marble or other decorative stones are joined to a support which is then fixed to the walls of the building. Such supports could be made of aluminium foam, replacing some of the expensive honeycombs presently used. Balustrades of balconies have to satisfy rigorous safety regulations. Some of the materials used today are too heavy and are problematic in the case of fires. If they could be replaced by aluminium foam samples, some of the problems would be solved.

Aluminium foams or foam panels could be very helpful in reducing the energy consumption of elevators. Because of frequent acceleration and slowing down and the high speed of modern elevators, lightweight construction is an important issue. However, safety regulations often prevent an application of conventional lightweight construction techniques. Because aluminium foams can act as energy absorbers and as stiff structural material at the same time, these applications seem very promising.

Lightweight fire doors and hatches make use of the relatively poor thermal conductivity and fire resistance of some of the low density aluminium foams. Although the melting point of aluminium is fairly low (< 660°C), aluminium foams are surprisingly stable when exposed to an open flame owing to a strong oxidation under such conditions [282,283].

The properties of the foamable precursor material used in the powder compact melting route, i.e. the consolidated mixture of metal powder and blowing agent (see Section 2.1.3), can also be exploited. In order to fasten plugs in concrete walls, a piece of foamable aluminium is inserted into the borehole together with the plug. The foamable precursor material is then heated up locally, thus leading to its expansion. The foam generated this way will fill the gap between concrete and plugs and lead to a very strong bonding provided the density of the resulting foam is high enough.

4.2.6. *Machine construction*

There are some interesting applications for metallic foams in machine construction. Stiff foamed parts or foam-filled columns with reduced inertia and enhanced damping could replace axles, rolls or platforms presently made of conventional metal. Such components can be used in stationary drilling or milling machines, as well as in printing machines. Housings for small hand-held drilling or grinding machines offer some advantages over traditional housings such as an enhanced intrinsic damping. Foamed metal housings for electrical machines would add electromagnetic shielding to the performance spectrum of the material. The structural body of grinding discs could be also made of aluminium foam with the grinding material being bonded to its circumference. The intrinsic damping of the disc would help to avoid deleterious vibrations, a partially open porosity could serve as a reservoir for the material ground off. Aluminium foams have also been used as supports for telescope mirrors [175,284]. Other applications require a very light buoyant filling material of high strength for floaters measuring the filling level of hot or corrosive media. Since polymer foams cannot be used, floaters are employed that are made of thin welded titanium sheet constructions and contain a magnetic system for reading out their position. As such floaters are very expensive, they could be replaced by aluminium foam parts with a dense outer skin which could house the magnetic system, withstand external pressure and create the buoyancy needed.

4.2.7. *Sporting equipment*

Sport equipment is a rewarding field for applying new materials due to the high prices which are accepted in this sector. However, not many application ideas for cellular metals are in existence to the knowledge of the author. One example is shin-bone protectors for football players where the good energy absorption capacity of aluminium foams could be exploited.

4.2.8. *Biomedical industry*

Titanium or cobalt–chromium alloys are used for prostheses or dental implants because of their bio-compatibility. To ensure ingrowth of tissue, one usually produces a porous layer of the same or another bio-compatible material on the prosthesis by thermal spraying or other methods. Alternatively, one could use porous titanium or titanium foam for such applications and tailor the density distribution to meet the requirements concerning strength, moduli, etc. of such components. There is no unanimity of how implants must be designed to ensure maximum

endurance and functionality. According to one opinion, the modulus of dental implants has to match the modulus of the jaw bone. Knowing the relationship between modulus and density of metallic foams, one could easily manufacture implants with the appropriate adapted modulus, ensure bio-compatibility and stimulate bone ingrowth into the (open) porosity [215]. Magnesium foams could be used as bio-degradable implants which serve as load-bearing structure as long as the bone still grows but are gradually absorbed by the body in a later stage of reconvalescence [216].

4.3. Cellular metals for functional applications

Traditional powder metallurgy has created porous sintered metals for a wide scope of applications [199,200,285]. It is not surprising to find very similar applications for the cellular metals described in the present overview, provided they have a certain degree of open porosity.

4.3.1. Filtration and separation

There are two types of filters: filters holding back and separating solid particles or fibres dispersed in a liquid (suspensions) or filters holding back solid or liquid particles dispersed in a gas (smoke or fog, respectively). Examples of the first type are filters for cleaning recycled polymer melts, for removing yeast from beer, or for contaminated oil. The second type includes filtration of diesel fumes or water removal in air lines. Important filter properties are fine filtration capacity, good particle retention, cleanability, mechanical properties, corrosion resistance and cost. Some of the cellular metals described in the present article, e.g., in Sections 2.1.4, 2.2.4, 2.3, and 2.4, possess a combination of properties not covered by the traditional P/M materials and might therefore be considered as complementary to these materials.

4.3.2. Heat exchangers and cooling machines

Highly conductive foams based on copper or aluminium can be used as heat exchangers. In this case, open cell structures are needed such as the ones described in Section 2.1.4 and 2.2.5 [286]. Heat can be removed from or added to gases or liquids by letting them flow through the foam and cooling or heating the foam at the same time. Owing to the open porosity, pressure drops can be minimised. An example of such applications are compact heat sinks for cooling of microelectronic devices with a high power dissipation density such as computer chips or power electronics. Nowadays, fin-pin arrays are the standard solution in such cases. Metal foams can perform better if they are selected in a way that thermal conductivity is kept as high as possible with their flow resistance maintained as low as possible. These two requirements are contradictory, so a compromise has to be found. Questions of heat exchanger design are discussed in detail in Refs. [264,287].

Another application field for open cellular materials is transpiration cooling. The high surface area, low flow resistivity and good thermal conductivity of some of the materials used make them promising candidates for such purposes.

4.3.3. Supports for catalysts

The effectiveness of catalysis critically depends on a high interface area between the catalyst and the gases or liquids to be reacted. Therefore, the catalyst is either processed into a highly porous structure or, if this is not possible, applied to another porous system such as a porous ceramic material. Cellular metals could replace such ceramics even if they cannot compete with them concerning surface area because they exhibit other useful properties such as high ductility and thermal conductivity. One application concept includes the preparation of a thin sheet of corrosion resistant metal foam, filling this foam with a slurry containing the catalytic substance by rolling and finally curing at elevated temperatures [288]. The resulting catalyst has good mechanical integrity, i.e. even after many temperature cycles the catalyst does not leave the metal foam support. One application for such catalysts is for removing nitrogen oxides (NO_x) from the exhaust fumes of power plants.

4.3.4. Storage and transfer of liquids

One of the oldest applications of porous powder metallurgical materials is as self-lubricating bearings in which the oil is stored in the interstices between particles and is allowed to slowly flow out, thus replacing the used oil. Of course, some of the cellular materials described in this overview could fulfil the same function but with the advantage of having a higher storage volume than traditional P/M parts. The application is not limited to oil: water can be kept and slowly released for automatic humidity control. Perfume can be stored and allowed to evaporate slowly. Porous rolls can hold and distribute water or adhesives to surfaces. Transport of the liquid can be driven by capillary action alone or by excess pressure in the roll. Finally, very open metallic structures can be used to store fluids at a constant and uniform temperature at cryogenic conditions. Moreover, the foam can reduce undesired movements of the liquid in partially filled tanks (“anti-sloshing”) [10,175].

4.3.5. Fluid flow control

Porous materials can be used for controlling with flow of liquids and gases [200]. It is known that flow restrictors manufactured by powder metallurgy are more reliable and accurate than conventional micrometering valves. Because so many degrees of “openness” of cellular metals are available, one could find tailored solutions for even more applications by appropriately selecting a cellular metal. Metal foams have already been used as flow straighteners in wind tunnels [175] or flow distributors in valves [240].

4.3.6. Silencers

Components for dampening of sound, of pressure pulses or of mechanical vibrations are also common in industrial applications of powder metallurgy [200]. Materials with a certain degree of open porosity can be tailored to damp some frequencies selectively while they pass others. Sudden pressure changes occurring in compressors or pneumatic devices can be damped with porous sintered elements. Materials such as the investment cast foams described in Section 2.1.4 or the foams made by deposition (Section 2.3) could replace such traditional elements for reasons of cost and effectivity [240].

4.3.7. Spargers

Some applications require that a gas be introduced into a liquid homogeneously and at a constant rate. An example of such an application is the carbonation of beverages. This operation requires a porous part that creates sufficiently small gas bubbles and satisfies criteria such as corrosion, heat or shock resistance. Porous metals can be a superior solution compared to other materials such as porous ceramics.

4.3.8. Battery electrodes

Lead foams could serve as supports for the active material in lead acid batteries in replacement of conventional lead gratings, thus allowing for constructing very light electrodes. The electrochemically active mass, a paste containing very fine lead oxide powders, could be filled into the open voids of a lead foam where it would contact the electrolyte (sulfuric acid). The lead foam acts as a highly conductive lattice leading to a low internal resistance of the battery. The nickel foams described in Sections 2.3 and 2.4 are already used as electrodes in pasted rechargeable NiCd batteries where weight savings and a higher energy density can be achieved [245,289]. Porous P/M materials with their extremely high surface area are being used in fuel cells [200,245].

4.3.9. Flame arresters

Cellular metals with high thermal conductivities of the cell wall material can be used to stop flame propagation in combustible gases. Open-cell foams of the type described in Section 2.3 have been shown to be capable of arresting flames even when they were travelling at velocities up to 550 m/s. In practice, long runs of pipes transporting combustible gases are protected close to possible sources of ignition so that, if ignition does occur, the flame cannot accelerate to high velocities [240].

4.3.10. Electrochemical applications

Nickel foams can be used as electrode material in electrochemical reactors. In filter-press electrodes a stack of isolated metal plates is used. The plates are separated by a turbulence-promoting plastic mesh and insulating membranes. If these meshes are replaced by sheets of cellular nickel with open channels (with each sheet attached to one of these plates), one increases the electrode surface while maintaining the turbulence promotion [290]. The reactors can be built more compactly this way. Nickel foams can also be used to improve electro-catalytic processes such as the electro-oxidation of benzyl alcohol assisted by NiOOH, which is electro-generated on nickel anodes. Packed beds of nickel foams were shown to improve the performance of such reactors [291].

4.3.11. Water purification

Cellular metallic materials could be used to reduce the concentration of undesired ions dissolved in water. In this application, the contaminated water flows through a highly porous cellular metal with an open structure. The ions react with the matrix metal of the cellular structure in a redox reaction. An electroless reduction of Cr(VI) ions by cast aluminium foams (see Section 2.1.4) was investigated in the literature [292].

4.3.12. Acoustic control

A sound wave control device can be obtained if one creates a lens- or prism-shaped part from a rigid open cell material, e.g. a metal foam. The sound waves will then be guided and redirected by this acoustic device [293]. Moreover, closed cell foams have been studied for their suitability as impedance adaptors for ultrasound sources.

4.4. Cellular materials for decoration and arts

Ever since metal foams have been known, these new materials have sparked the imagination of designers and artists. The primary objective of decorative or artistic applications is to create a distinct visual or haptic impression compared to that of conventional materials. Foams based on gold or silver are thought to be a potential new material for jewellery to gain an unprecedented visual appearance or a large volume with a correspondingly low weight. Aluminium foams have been used to build fancy furniture, clocks, lamps, etc. [294]. If chairs or tables are manufactured with aluminium foam, the mechanical performance is certainly paramount, whereas for many other applications the actual physical or mechanical properties are of minor importance. High-priced loudspeaker systems have been made from aluminium foam. The foam not only provides a high specific stiffness and moderate mechanical damping, but also a “high-tech” image that may appear more attractive than conventional materials. For the materials scientist, such applications may not be very satisfying because they are partially based on the fact that the material is “fashionable”, an effect that may wear off quickly. However, as the price of the material is not so important for design applications, this can be a good opportunity to establish new manufacturing methods.

4.5. General aspects of selecting applications

It is often quite difficult to find applications for a new material. This applies to cellular metals and metal foams as well. Discussions in recent years have shown that the most promising applications are those where one makes use of various properties of metals foams. If only the low weight of the material is of interest, there will most probably already exist an established, cheaper material. If, however, low weight combined with good energy absorption characteristics or heat resistance is required, then the competitiveness of metal foams will be significantly increased. Therefore, each new application idea has to be first evaluated by identifying the essential properties which are needed. Then one has to determine whether there is a cellular metal with the desired spectrum of properties and whether any established materials exist with comparable properties. If this is the case, other criteria such as cost will have to be considered to decide which solution is preferable.

5. Summary

Recent technological advances have led to an increased availability of production processes for a wide range of cellular metals and alloys. Open and closed pore

morphologies and relative densities ranging from 50 to 98% can be achieved. In contrast to many of the materials available before, cellular metals which can be produced nowadays are less expensive, therefore being suited for wide-ranging applications in mass markets. Such applications that include structural applications in various industrial sectors — automotive, aerospace, machine construction, etc. — as well as functional applications, are now being considered or already carried out.

Current research on the improvement of the production processes concentrates on improving process control to produce higher quality materials and to achieve a better reproducibility and predictability of their properties. By “better quality” one usually means a good morphological and structural homogeneity of the cellular materials. For structural applications, curved or corrugated cell walls, “dead” inclusions, ruptured or missing cell walls, or other defects have to be avoided, whereas pore size distribution seems to be less important [264,295–297]. For functional materials, a uniformity of pore or inter-pore channel size may be important.

For most processes, there is no applicable theoretical or numerical model at the moment which allows for predicting the effect of parameter changes. Improvements have to be made by “trial and error” in many cases. With good process models, the improvement of production methods could be accelerated.

Cost reduction is also an important issue in current developments. Using cheaper starting materials, omitting or combining processing steps, and reducing scrap during production are the usual strategies. With some of these improvements coming into reality, there is some hope that in the very near future industrial mass market applications will be realised which in turn will trigger other use of cellular metallic materials.

Acknowledgements

The author would like to thank the following persons for contributing with photographic material, drawings, data or other assistance: O. Andersen, T. Baumbach, V. Belyi, M. Bram, F. Chen, H. von Hagen, M. Hartmann, R. Mitchell, T. Miyoshi, V. Paserin, F. Schörghuber, D. Schwartz, V. Shapovalov, D. Sypeck, L. Tuchinskiy and I. Wagner.

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